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Volcanic Suites and Related Cauldrons of Timber Mountain-Oasis Valley Caldera Complex, Southern Nevada

By F. M. BYERS, JR., W. J. CARR, PAUL P. ORKILD, W. D QUINLIVAN, *and* K. A. SARGENT

GEOLOGICAL SURVEY PROFESSIONAL PAPER 919

Prepared in cooperation with the U.S. Atomic Energy Commission

Stratigraphic, petrochemical, and structural relations of igneous rocks of Timber Mountain-Oasis Valley caldera complex, including calc-alkalic rocks from Silent Canyon caldera, southwestern Nevada volcanic field

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1976

102.8

UNITED STATES DEPARTMENT OF THE INTERIOR

THOMAS S. KLEPPE, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress Cataloging in Publication Data
Main entry under title:
Volcanic suites and related cauldrons of Timber Mountain–Oasis Valley caldera complex, southern Nevada.
(Geological Survey Professional Paper 919)
"Prepared in cooperation with the U.S. Atomic Energy Commission."
Bibliography: p.
Supt. of Docs. no.: I 19.16:919
1. Volcanic ash, tuff, etc.–Nevada–Nye Co. 2. Calderas–Nevada–Nye Co.
I. Byers, Frank M., 1916– II. United States. Atomic Energy Commission. III. Series: United States Geological Survey Professional Paper 919.
QE461.V63 552'.2'0979334 76-608057

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402
Stock Number 024-001-02868-9

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METRIC-ENGLISH EQUIVALENTS

Metric unit			English equivalent
Length			
ilimetre (mm)	=	0.03937	inch (in)
re (m)	=	3.28	feet (ft)
metre (km)	=	.62	mile (mi)
Area			
are metre (m^2)	=	10.76	square feet (ft^2)
are kilometre (km^2)	=	.386	square mile (mi^2)
tare (ha)	=	2.47	acres
Volume			
ic centimetre (cm^3)	=	0.061	cubic inch (in^3)
e (l)	=	61.03	cubic inches
ic metre (m^3)	=	35.31	cubic feet (ft^3)
ic metre	=	.00081	acre-foot (acre-ft)
ic hectometre (hm^3)	=	810.7	acre-feet
e	=	2.113	pints (pt)
e	=	1.06	quarts (qt)
e	=	.26	gallon (gal)
ic metre	=	.00026	million gallons (Mgal or 10^6 gal)
ic metre	=	6.290	barrels (bbl) (1 bbl = 42 gal)
Weight			
m (g)	=	0.035	ounce, avoirdupois (oz avdp)
m	=	.0022	pound, avoirdupois (lb avdp)
ne	=	1.1	tons, short (2,000 lb)
ne	=	.98	ton, long (2,240 lb)
Specific combinations			
gram per square ntimetre (kg/cm^2)	=	0.96	atmosphere (atm)
gram per square ntimetre	=	.98	bar (0.9869 atm)
ic metre per second (m^3/s)	=	35.3	cubic feet per second (ft^3/s)

Metric unit			English equivalent
Specific combinations—Continued			
litre per second (l/s)	=	.0353	cubic foot per second
cubic metre per second per square kilometre [(m^3/s)/km^2]	=	91.47	cubic feet per second per square mile [(ft^3/s)/mi^2]
metre per day (m/d)	=	3.28	feet per day (hydraulic conductivity) (ft/d)
metre per kilometre (m/km)	=	5.28	feet per mile (ft/mi)
kilometre per hour (km/h)	=	.9113	foot per second (ft/s)
metre per second (m/s)	=	3.28	feet per second
metre squared per day (m^2/d)	=	10.764	feet squared per day (ft^2/d) (transmissivity)
cubic metre per second (m^3/s)	=	22.826	million gallons per day (Mgal/d)
cubic metre per minute (m^3/min)	=	264.2	gallons per minute (gal/min)
litre per second (l/s)	=	15.85	gallons per minute
litre per second per metre [(l/s)/m]	=	4.83	gallons per minute per foot [(gal/min)/ft]
kilometre per hour (km/h)	=	.62	mile per hour (mi/h)
metre per second (m/s)	=	2.237	miles per hour
gram per cubic centimetre (g/cm^3)	=	62.43	pounds per cubic foot (lb/ft^3)
gram per square centimetre (g/cm^2)	=	2.048	pounds per square foot (lb/ft^2)
gram per square centimetre	=	.0142	pound per square inch (lb/in^2)
Temperature			
degree Celsius (°C)	=	1.8	degrees Fahrenheit (°F)
degrees Celsius (temperature)	=	[(1.8 × °C) + 32]	degrees Fahrenheit

VOLCANIC SUITES AND RELATED CAULDRONS OF TIMBER MOUNTAIN-OASIS VALLEY CALDERA COMPLEX, SOUTHERN NEVADA

By F. M. Byers, Jr., W. J. Carr, Paul P. Orkild, W. D. Quinlivan, and K. A. Sargent

ABSTRACT

The Timber Mountain-Oasis Valley caldera complex occupies a slightly elliptical area about 40 km (25 mi) in maximum diameter in southern Nye County, Nev., and is a major part of the southwestern Nevada volcanic field, which includes peralkaline, alkali-calcic, calc-alkalic, and calcic centers. Upper Miocene and lower Pliocene calc-alkalic and alkali-calcic ash-flow sheets and petrologically related igneous rocks of the Timber Mountain-Oasis Valley caldera complex were erupted 16-9 m.y. (million years) ago and were associated with multiple cauldron subsidences.

The newly named calc-alkalic Redrock Valley and Crater Flat Tuffs were associated with collapses 16-14 m.y. ago, possibly within the Sleeping Butte caldera, only a small part of which is still exposed. The Redrock Valley consists of only one known cooling unit, whereas the Crater Flat consists of two newly named members, the Bullfrog and the Prow Pass.

The quartz-bearing Stockade Wash Tuff, formerly the Stockade Wash member of the quartz-poor Paintbrush Tuff, is here raised to separate formational rank. It is a calc-alkalic tuff, erupted between 13.8 and 13.2 m.y. ago as a late effusive from the dominantly peralkaline Silent Canyon caldera. The Stockade Wash is unrelated to the Paintbrush, in both its petrologic features and volcanic source, but is closely similar petrographically to two other late ash-flow sheets of limited extent within and around Silent Canyon caldera and also to 1,500 m (5,000 ft) of calc-alkalic tuffs and rhyolite lavas of Area 20, which fill Silent Canyon caldera.

The Paintbrush Tuff is here restricted to include the quartz-free to quartz-poor bedded and intercalated welded ash-flow tuffs that occur between the underlying redefined Stockade Wash Tuff, or the tuffs and rhyolites of Area 20, and the overlying Timber Mountain Tuff. The Paintbrush is a major alkali-calcic volcanic sequence of genetically related bedded tuff and ash-flow tuff sheets that were erupted 13.2-12.5 m.y. ago from the Claim Canyon cauldron center, the southernmost part of which is exposed in an arcuate segment at the south side of the complex. The ash-flow sheets consist of (1) the Topopah Spring Member near the base, (2) the Pah Canyon Member, (3) a local subsurface unit that may grade upward into a lava flow, (4) the Yucca Mountain Member, (5) the Tiva Canyon Member, which includes the intracauldron tuff of Chocolate Mountain, and (6) the intracauldron tuff of Pinyon Pass.

The Claim Canyon cauldron segment exposes greatly thickened intracauldron facies of Paintbrush welded tuffs, intercalated lavas, and tuff breccia. The estimated volume of the Topopah Spring Member is about 250 km³ (60 mi³), but may be much greater, as the unit is buried by younger welded tuffs and lavas within the exposed segment of the cauldron. The post-Topopah Spring ash-flow sheets of the Paintbrush Tuff and intercalated lavas are more than 1,500 m thick in the Claim Canyon cauldron segment. This thick post-Topopah Spring intracauldron filling implies considerable structural depression inside the cauldron. It seems unlikely that this much structural depression could have occurred within the cauldron following the eruption of only the Topopah Spring Member. We interpret the exposed Claim Canyon cauldron segment as probably recording continued episodic subsidence during or immediately following eruption of each ash-flow sheet of the Paintbrush. The maximum subsidence of Claim Canyon cauldron probably occurred during the last stages of eruption of 1,000 km³ (250 mi³) of the Tiva Canyon Member. An alternative interpretation infers that subsidence at the Oasis Valley caldera segment was related to eruption of the Tiva Canyon. A thick tuff breccia along and near the wall of the Claim Canyon cauldron segment, however, grades laterally and vertically into welded masses of the Tiva Canyon and may mark a locus of Tiva Canyon volcanic vents.

Cauldron resurgence possibly affected the Claim Canyon cauldron, as the tuffs filling the exposed Claim Canyon cauldron segment now stand topographically and structurally high; the buried larger part of the cauldron to the north has been dropped to great depth by collapses of the younger Timber Mountain caldera. Alternatively, the segment was raised with a much larger Yucca Mountain block during early broad doming of Timber Mountain caldera prior to eruption of the Timber Mountain Tuff.

The lower Pliocene alkali-calcic Timber Mountain Tuff is redefined to include all quartz-bearing ash-flow tuff sheets and minor interbedded ash-fall tuff erupted about 11 m.y. ago from the Timber Mountain caldera center. The tuff includes in ascending order, the Rainier Mesa and Ammonia Tanks Members, which are the two widespread ash-flow sheets of the original definition, and the newly added intracaldera tuffs of Buttonhook Wash and Crooked Canyon. The Ammonia Tanks Member has been further redefined to include the local tuffs of Cat Canyon and Transvaal, which are now known to be equivalent to part or all of the Ammonia Tanks.

Two major subsidences of Timber Mountain caldera were associated with eruption of the Rainier Mesa Member, having a volume of more than 1,200 km³ (300 mi³), and with the eruption of the overlying Ammonia Tanks Member, having a volume of about 900 km³ (230 mi³). The tuff exposed on the central resurgent dome of Timber Mountain caldera is intracaldera Ammonia Tanks, more than 900 m (3,000 ft) thick, and was formerly mapped as tuff of Cat Canyon. Thicknesses in excess of 450 m (1,500 ft), granophyric texture, and fluidal flow banding of both the Rainier Mesa and Ammonia Tanks Members within the Oasis Valley caldera segment suggest also partial collapse of that segment during eruption of the members, forming a large volcano-tectonic depression. The area that collapsed because of the eruption of the Rainier Mesa is somewhat larger than that which collapsed because of the Ammonia Tanks, as might be expected from the greater volume of the Rainier Mesa.

The Timber Mountain resurgent dome in the central area of Timber Mountain caldera contains both inward-dipping high-silica rhyolite tuff dikes, possibly cone sheets, and an outward-dipping microgranitic ring

dike approaching quartz latite composition (68 percent silica). These two rock types are petrologically similar to limiting compositions of the Ammonia Tanks Member and may have come from different levels of a zoned silicic magma chamber high in the crust.

Post-Timber Mountain alkali-calcic tuffs and related lavas are confined to the Oasis Valley-Timber Mountain caldera complex and probably were erupted 11.0-9.5 m. y. ago from within the Oasis Valley caldera segment.

Rhyolite lavas extruded from the rim and moat areas of Timber Mountain caldera concluded the activity of the caldera complex about 9 m. y. ago.

INTRODUCTION

The ash-flow sheets discussed in this report constitute the major stratigraphic units shown on the U.S. Geological Survey map of the Timber Mountain caldera area (Byers and others, 1976) in the Nevada Test Site region of southern Nevada. An attempt is made to relate the tuff sheets and petrologically similar lavas and intrusives to major volcanic centers of the Timber Mountain-Oasis Valley caldera complex (fig. 1). A closely related paper (Christiansen and others, 1975) emphasizes the structural setting and associated Tertiary volcanism in the region around the caldera complex.

Present knowledge of the relations and distribution of volcanic rocks in the Nevada Test Site region of southwestern Nevada is based on 34 geologic quadrangle maps (fig. 2), about 30 exploratory drill holes, several Bouguer gravity (Don L. Healey, written commun., 1968) and aeromagnetic maps (G. D. Bath, written commun., 1968), more than 500 polarity determinations of natural remanent magnetism of rocks (G. D. Bath, written commun., 1965-68), radiometric age determinations of 51 volcanic rocks (Kistler, 1968; Marvin and others, 1970), and more than 400 modal analyses of thin sections.

During the concentrated effort of geologic mapping from 1960 to 1964, the volcanic rocks at the Nevada Test Site were grouped into formations because of the need to define stratigraphic units for the geologic maps (fig. 2). Ash-flow tuff sheets of similar mineralogy and chemistry were grouped into formations, the individual sheets being members of the formations (Smith, 1960a, p. 812-813; R. L. Smith, oral commun., 1960-68; Christiansen and others, 1969), but some stratigraphic divisions were based on limited knowledge regarding areal distributions of the units and their associations with major volcanic centers. In this paper the geologic and petrologic relations of the tuff sequences to lavas and intrusives at caldera centers are further emphasized in arriving at a logical basis for redefining some of the units.

ACKNOWLEDGMENTS

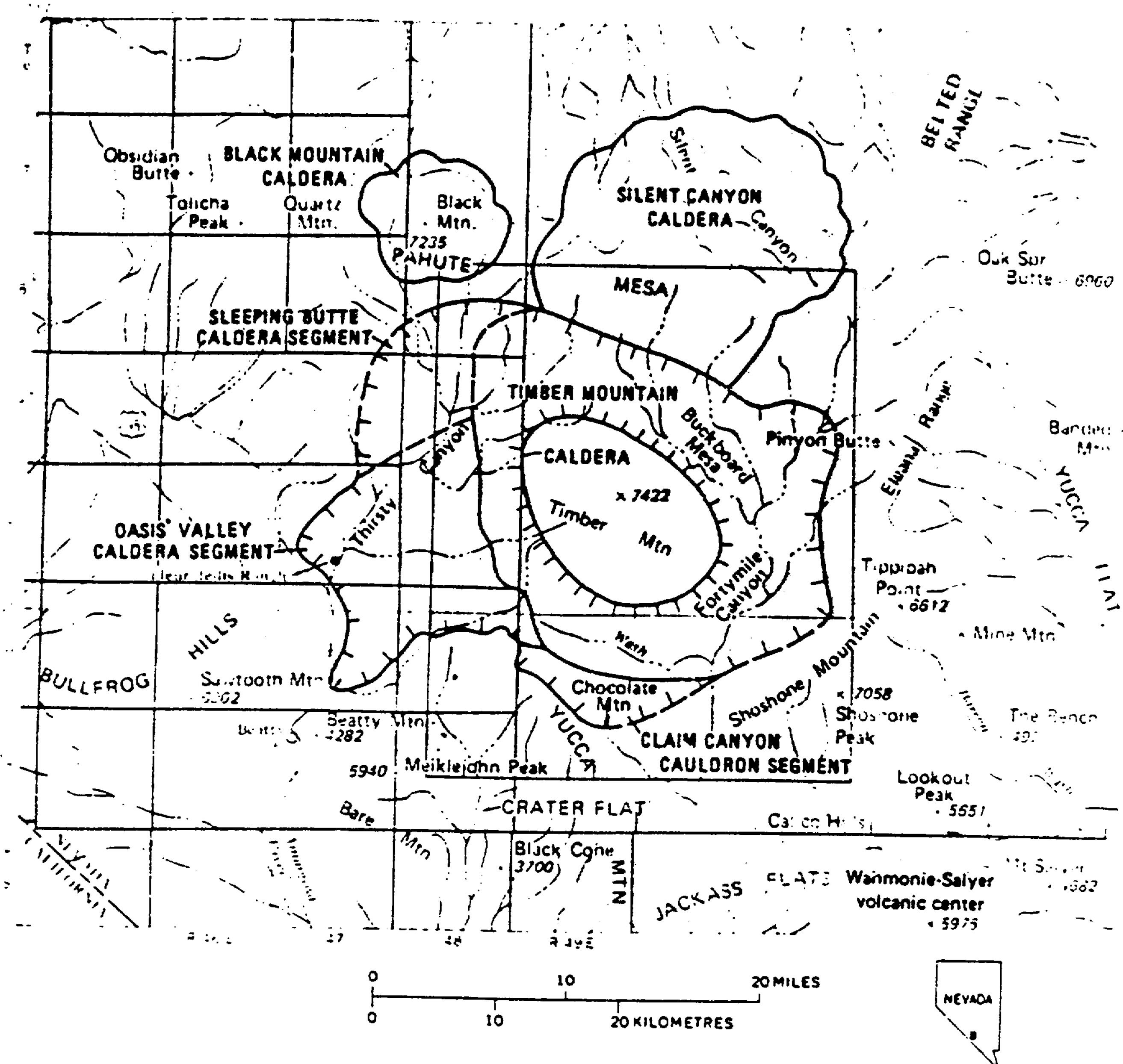
Several geologists have contributed materially to this report by supplying us with basic data and interpretation. R. L. Smith helped us define and solve many of the caldera problems through field conferences. D. L. Healey and G. D. Bath contributed gravity and aeromagnetic interpretation, which greatly aided in delineating the outlines of the buried caldera structures in figure 1. D. C. Noble contributed to the interpretation of volcanic history and location of the caldera boundaries. J. T. O'Connor supplied about 50 thin-section modes of the tuffs. Our colleagues R. E. Anderson, R. L. Christiansen, E. B. Ekren, and P. W. Lipman provided geologic information and stimulating discussion. We, however, assume full responsibility for any errors or misinterpretations of the data. This work was fully supported by the U.S. Atomic Energy Commission.

NOMENCLATURE

In general, we follow guidelines of the ash-flow tuff nomenclature of Smith (1960a, p. 800-801; 1960b) and Ross and Smith (1961). For brevity in this report and on the geologic map of the Timber Mountain area (Byers and others, 1976) ash-flow tuff (Ross and Smith, 1961, p. 3) or simply the word "tuff" in the proper context carries the genetic connotation of ash-flow cooling unit of Smith (1960a, p. 801), as well as that of a lithologic term. A tuff or ash-flow cooling unit, in this connotation, was emplaced in an instant of geologic time and is therefore a time-marker as well as a lithologic unit (compare with Smith, 1960b, p. 150). The plural term "tuffs," analogous to "lavas" or "lava flows," is used for two or more ash-flow cooling units mapped as a unit (for example, Christiansen and Lipman, 1965; Sargent, 1969; Rogers and others, 1967). The singular term "tuff" is also used in formal stratigraphic nomenclature—for example, Paintbrush Tuff—in which it carries the dual genetic and lithologic implication just noted, inasmuch as the component tuff members and the informal tuffs are single ash-flow cooling units. "Ash-flow sheet" is also used descriptively in discussing the extensive cooling units of large volume associated with cauldron subsidence.

Other types of tuff are indicated in this report and on the Timber Mountain map (Byers and others, 1976) by appropriate modifiers (compare with Ross and Smith, 1961, p. 3), such as bedded tuff (descriptive) and ash-fall tuff (genetic).

In Smith's (1960b, p. 157-158) summary discussion of the cooling unit and composite sheet, he implied the existence of complete cooling breaks between cooling units and partial cooling breaks within compound cooling units by giving criteria for recognizing types of hiatuses between ash-flow units. Recognition of the nature of these hiatuses, herein referred to as either a partial or complete cooling break, is necessary in order to define an ash-flow cooling unit as the basic stratigraphic unit with time-marker implications (Smith, 1960a, pl. 1; Christiansen and others, 1968; Noble, Bath, and others 1968, p. C61).



EXPLANATION

Approximate outer limit of Timber Mountain-Oasis Valley caldera complex. Includes Sleeping Butte and Claim Canyon segments. Dashed where indefinite

Periphery of Timber Mountain resurgent dome

FIGURE 1.—Southwestern Nevada volcanic field, Nye County, Nev., showing location of Timber Mountain caldera and other major volcanic centers. Area shown on the geologic map by Byers and others (1976) is shaded.

A compositional subdivision of an ash-flow tuff sheet, characterized by a unique and laterally correlatable phenocryst assemblage, is called a subunit, following usage of Smith and Bailey (1966, p. 11) and Lipman, Christiansen, and O'Connor (1966). The term "caprock" (Lipman, Christiansen, and O'Connor, 1966, p. F5), although a topographic term, conveniently describes the more crystal-rich, commonly more mafic upper subunit of a compositionally zoned cooling unit. The caprock is so named because it commonly forms a resistant capping

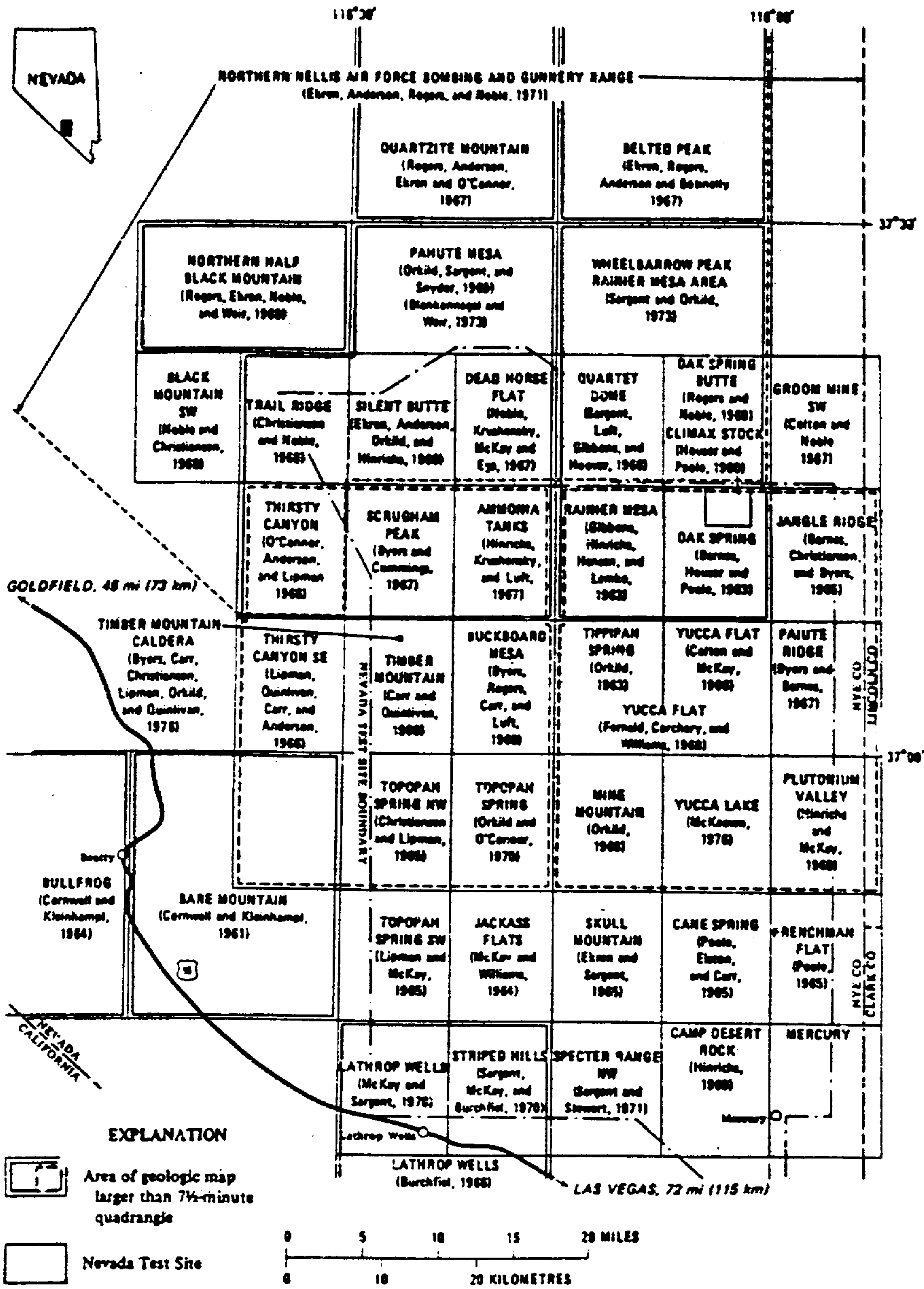


FIGURE 2.—Index showing original sources of geologic data and other maps published by the U.S. Geological Survey for the Timber Mountain caldera area, Nevada Test Site, and adjacent region. Mapped areas are identified by author and date and are listed in the references at the end of the text.

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-lge, which is the result of a densely welded zone overlying a less welded zone in a compound cooling unit. In many places the contact between compositional subunits is gradational within a foot or two and commonly nearly coincides with the contact between welding and crystallinity zones.

The Paintbrush Tuff and younger silicic volcanic rocks of the Timber Mountain-Oasis Valley caldera complex are alkali-calcic in the Peacock (1931) classification and do not readily fit some of the commonly used classifications (Rittmann, 1952; Nockolds, 1954; O'Connor, 1965). In order to emphasize the differences in chemical composition among these younger rocks of the Timber Mountain area (W. D. Quinlivan and P. W. Lipman, written commun., 1974), tuffs and lavas ranging from about 65 to 72 percent SiO_2 are called quartz latites; rocks ranging from about 72 to 76 percent silica are called rhyolites or low-silica rhyolites to emphasize compositional range; and rocks in the range from about 76 to 78 percent silica are called high-silica rhyolites. The pre-Paintbrush volcanic rocks are normal calc-alkalic rhyolites, which are lower in total alkalis, particularly potassium, and slightly higher in lime than younger rocks of similar silica content. Peralkaline rocks (Shand, 1947, p. 229) are represented by the early effusives of Silent Canyon caldera and contain sodium in pyroxene and amphibole, as well as in feldspar. These rocks are considered briefly in this report.

The terms "caldera" and "cauldron" are used in this paper to emphasize topographic expression. Caldera is used in the sense proposed by Williams (1941, p. 242) for a large, roughly circular or oval topographic depression in the central area of a volcano or volcanic complex. We also recognized filled and buried calderas. The Silent Canyon caldera no longer has the topographic form of a caldera, but it is filled with low-density volcanic rocks that make a large gravity anomaly having the shape of a caldera (D. L. Healey and C. H. Miller, written commun., 1967; Orkild and others, 1968, fig. 2). The term "cauldron" is used for a generally circular or oval. structural block which has subsided in the area of a volcanic or intrusive center but which has lost through subsequent erosion any topographic features of the former caldera. Our usage is virtually synonymous with "cauldron subsidence" as defined in the study of Glen Coe cauldron by Clough, Maufe, and Bailey (1909). The term "segment" is applied to a portion of a caldera or cauldron that does not have a circular form either because a part of it has been truncated by a later adjacent subsidence or because its original form has been severely modified by later structural movement.

The term "volcanic center" is occasionally used herein for the entire volcanic edifice including the underlying magma chamber, the subsided cauldron, the surficial caldera, if preserved, and the extrusive vents that are served as dikes and vent breccias. The intimate association of central stocks, ring dikes, and cone sheets with cauldron structures has been emphasized many times in the literature, notably in review papers by Richey (1932), Richey, MacGregor, and Anderson (1961), Anderson (1936), Billings (1943), Buddington (1959, p. 680–685), Smith, Bailey, and Ross (1961), Branch (1966), Hamilton and Myers (1967, p. C6–C9), and Eggler (1968, p. 1555–1557).

GENERAL GEOLOGIC RELATIONS

The southwestern Nevada volcanic field (fig. 1) comprises upper Tertiary effusive rocks from the Timber Mountain-Oasis Valley caldera complex, rocks from peralkaline calderas in the northern part, and several minor satellite lava piles ranging from calc-alkalic to calcic (Noble and others, 1965; Christiansen and others, 1976). The ash-flow tuffs and related rocks discussed in this report constitute most of a thick upper Miocene and lower Pliocene calc-alkalic and alkali-calcic volcanic sequence shown on the geologic map of the Timber Mountain caldera area (Byers and others, 1976) and include all the known silicic eruptive products of the Timber Mountain-Oasis Valley caldera complex. Peralkaline volcanic rocks of the Silent Canyon and Black Mountain calderas to the north (fig. 1) intertongue and postdate, respectively, the tuffs and lavas of this report and have been discussed elsewhere (Noble and others, 1963, 1965; Sargent and others, 1965; Christiansen and Noble, 1965; Noble, Sargent, and others, 1968; Christiansen and others, 1976).

The newly named upper Miocene Redrock Valley and Crater Flat Tuffs (table 1) are calc-alkalic effusives of probably the oldest recognizable caldera within the

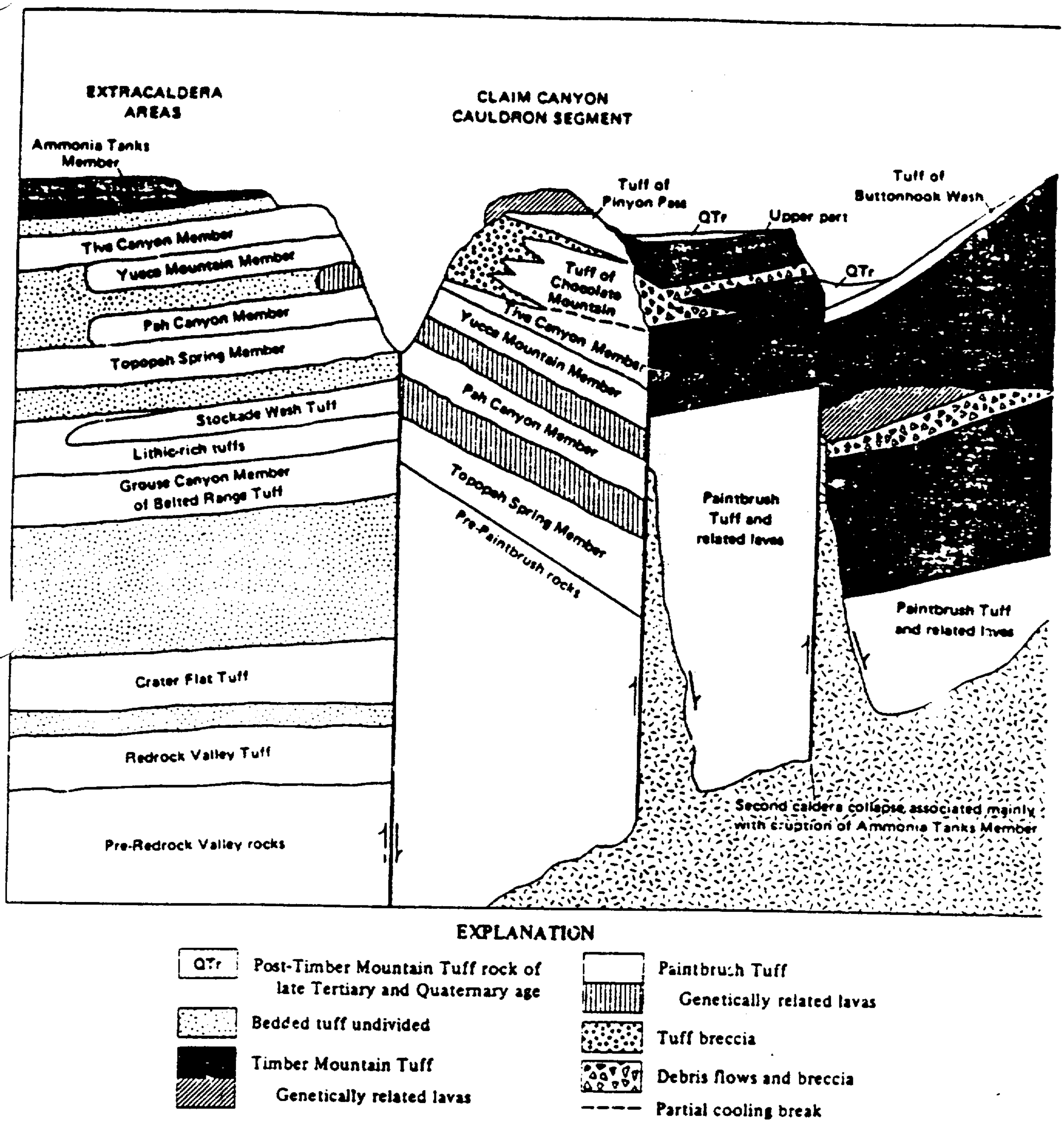
TABLE 1.—*Generalized stratigraphic nomenclature of tuff formations and members as herein redefined and their indicated volcanic center*

[Minor intracaldera informal units are omitted]

Age	Volcanic center	Formation	Member or unit
Pliocene	Timber Mountain Caldera	Timber Mountain Tuff[1]	Tuffs of Crooked Canyon[1] Tuff of Buttonhook Wash[1] Ammonia Tanks Member[1] Rainier Mesa Member
Miocene	Claim Canyon Cauldron	Paintbrush Tuff[1]	Tuff of Pinyon Pass Tiva Canyon Member Yucca Mountain Member Pah Canyon Member Topopah Spring Member
	Silent Canyon Caldera	Stockade Wash Tuff[2]	
	Sleeping Butte Caldera	Crater Flat Tuff[2]	Prow Pass Member[2] Bullfrog Member[2]
		Redrock Valley Tuff[2]	

[1]Geologic name redefined.

[2]New geologic name.



Timber Mountain–Oasis Valley caldera complex. Only a small part of this caldera is now exposed and is herein called the Sleeping Butte caldera segment (fig. 1). The redefined Stockade Wash Tuff (table 1) is not a product of • Timber Mountain caldera complex but is a late calc-alic ash-flow sheet of the dominantly peralkaline Silent Canyon caldera. The overlying Paintbrush Tuff, as herein defined, consists of several quartz-poor densely welded ash-flow tuff cooling units that are lithologically and petrologically distinct from those of the formations above and below. Most of the units are exposed within the Claim Canyon cauldron segment (fig. 1), where they are very thick and intertongue with petrologically similar rhyolite lavas. The uppermost formation, the Timber Mountain

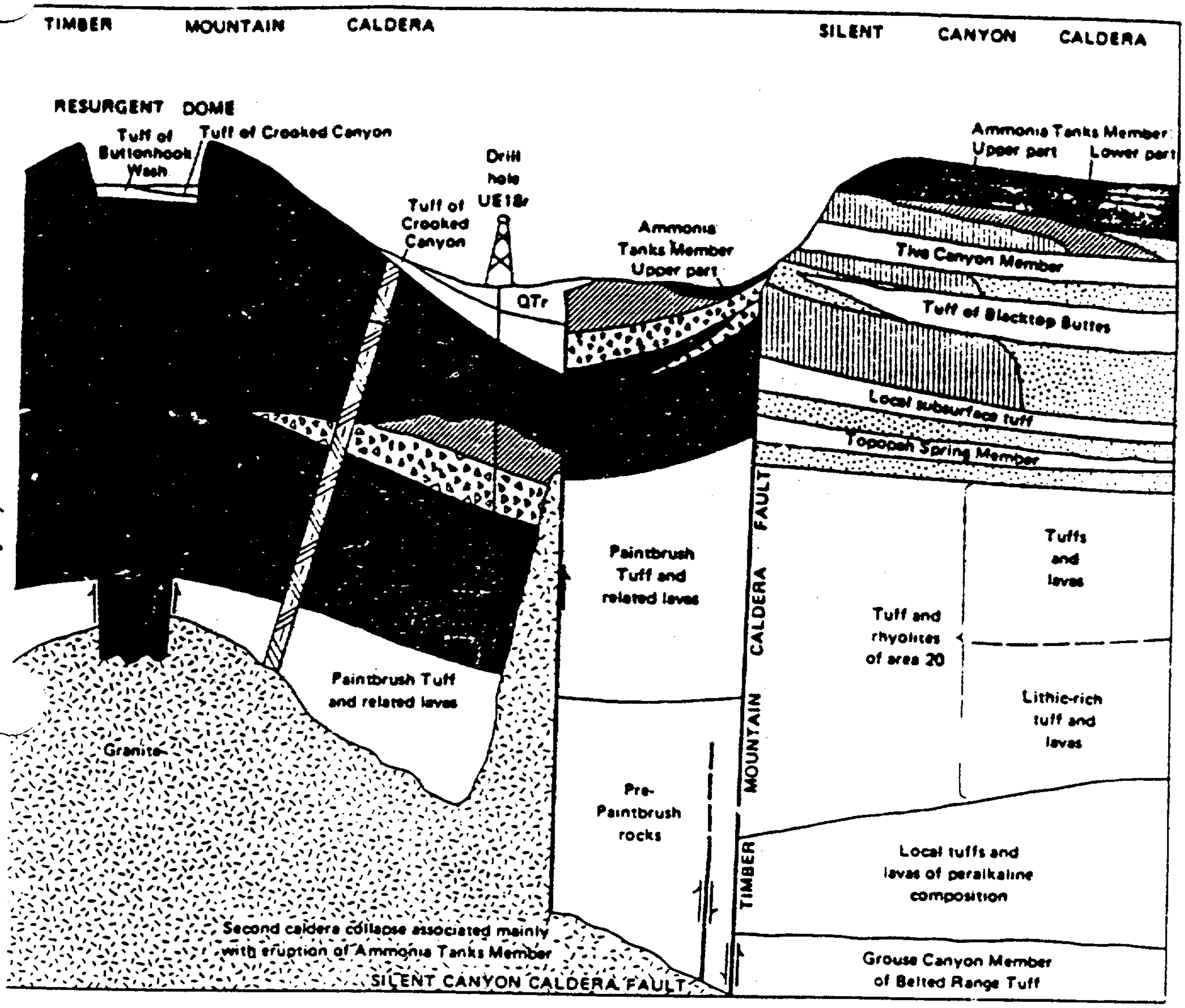


FIGURE 3 (left and above).—Generalized schematic diagram through southwestern Nevada volcanic field, showing geologic relations between ash-flow tuff sheets and related rocks discussed in this report. A few minor units omitted. Length of diagram about 50 km (30 mi).

Tuff, contains common to abundant quartz phenocrysts and consists of two widespread coextensive members, the Rainier Mesa and the overlying Ammonia Tanks. Within parts of the Timber Mountain caldera these two members thicken, intertongue with rhyolite lavas, and are overlain by intracaldera informal units of the Timber Mountain Tuff, as herein redefined. Post-Timber Mountain tuffs and lavas are of relatively small volume and are largely confined to the Timber Mountain-Oasis Valley caldera complex. The stratigraphic and geologic relations of the flow tuffs and intercalated rhyolite lavas in the southern Nevada volcanic field are shown in figure 3.

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TUFFS AND LAVAS RELATED TO SLEEPING BUTTE CALDERA

REDROCK VALLEY TUFF

The Redrock Valley Tuff, the oldest ash-flow sheet related to the Timber Mountain-Oasis Valley caldera complex, is here named after exposures in Redrock Valley (fig. 4). The least altered and most complete exposure, however, is on the west side of Yucca Flat at hill 5504, 2.4 km (1.5 mi) east of the head of Redrock Valley (fig. 4) in the northern part of the Tippipah Spring quadrangle (Orkild, 1963) and is designated the type locality. The unit, as now

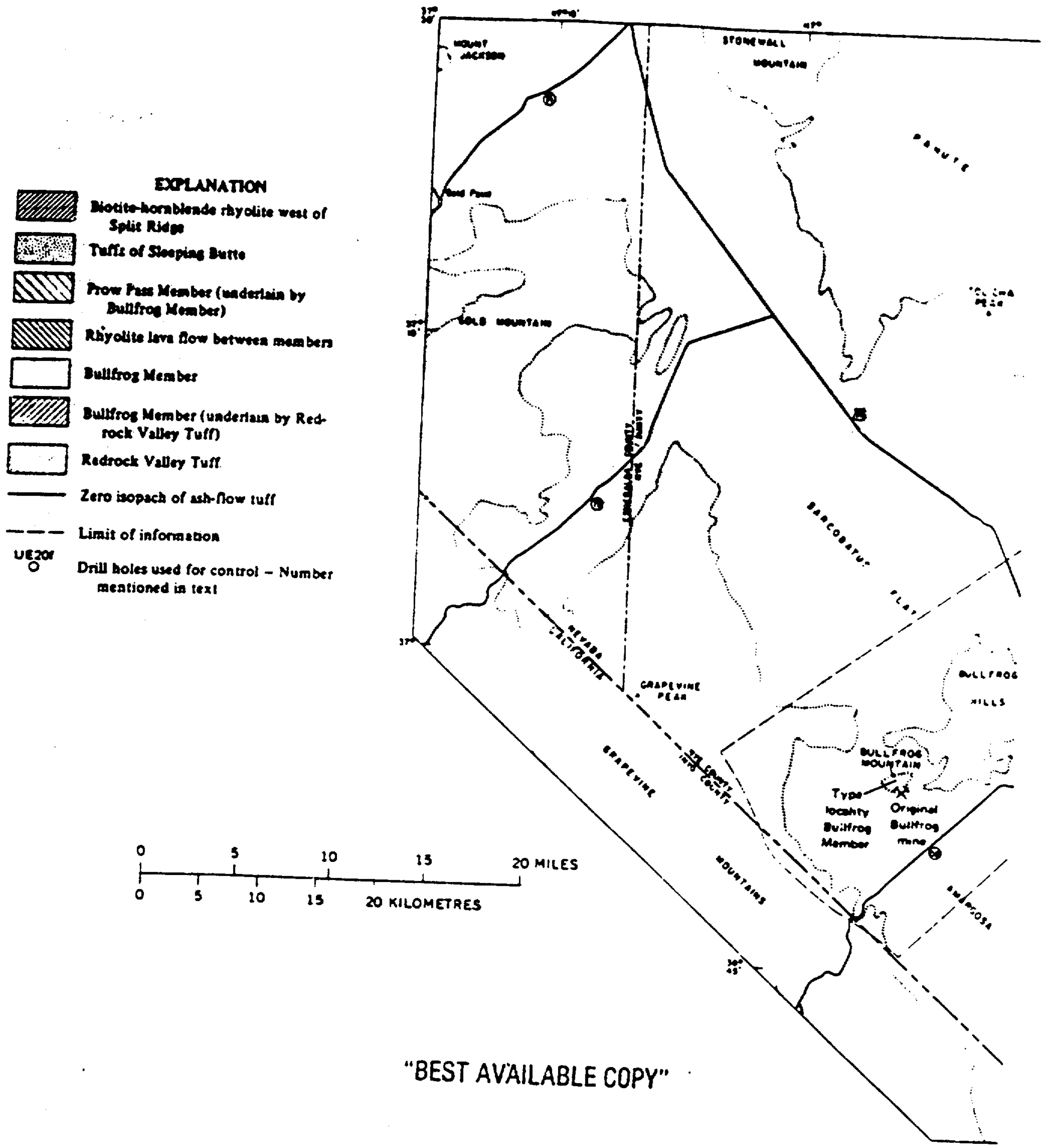
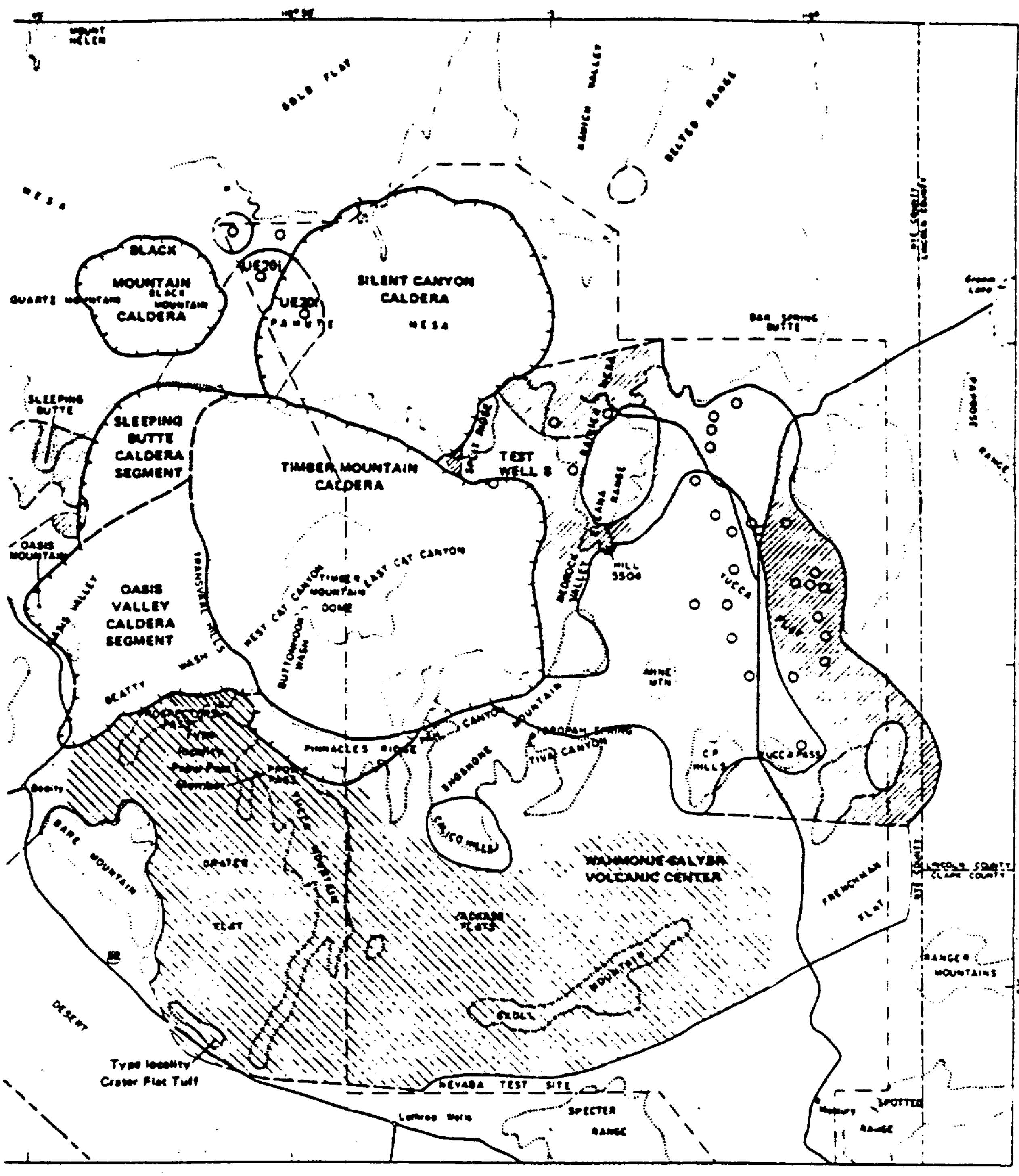


FIGURE 4.—Areal distribution of Redrock Valley Tuff, members of Crater Flat

known, consists of only one ash-flow tuff cooling unit and has been informally called "tuff of Redrock Valley" (Marvin and others, 1970, p. 2659, 2667). The Redrock Valley Tuff is the oldest known volcanic rock that originated from the Timber Mountain-Oasis Valley caldera complex.

The known extent of the Redrock Valley Tuff is shown in figure 4. At hill 5504 the unit is approximately 125 m



Tuff, and other volcanic rocks that are probably related to Sleeping Butte caldera.

(400 ft) thick. It reaches a maximum thickness of 418 m (1,370 ft) where penetrated in test well 8 and is about 300 m (1,000 ft) thick in two wells west and south of Rainier Mesa. Where penetrated in other drill holes (fig. 4), it ranges in thickness from about 30 to 210 m (100–700 ft).

The tuff is exposed at the surface in three widely scattered localities besides the one northwest of Yucca Flat. The most significant of these is a small outcrop 5 km (3 mi) south of Sleeping Butte near the intersection of Sleeping ·te and Oasis Valley caldera segments (fig. 4); this ›sure is the only one known on the west side of the caldera complex. The northernmost exposure at the south end of the Belted Range was locally mapped in Quartet Dome quadrangle (fig. 2; Sargent and others, 1966) as "ash-flow tuff of Kawich Valley." North of Frenchman Flat the nonwelded distal edge of the Redrock Valley Tuff is exposed in a few fault blocks along the border between Nye and Lincoln Counties.

Little is known of the original total extent of the Redrock Valley Tuff, but if the unit was as widespread as suggested by the scattered outcrops and drill holes, as much as 360 km³ (90 mi³) may be present outside the Timber Mountain–Oasis Valley caldera complex, assuming an average thickness of 120 m (400 ft) over 3,000 km² (1,200 mi²). The volume of tuff buried beneath the Timber Mountain–Oasis Valley caldera complex would not increase this figure significantly in view of the inferred wide areal extent and the uncertainties involved.

The Redrock Valley Tuff rests on Paleozoic rocks in the Eleana Range or on a thin, bedded unnamed tuff sequence immediately overlying the Fraction Tuff (Rogers and others, 1967; Marvin and others, 1970) in drill holes of the Rainier Mesa and Yucca Flat areas shown in figure 4. The tuff is overlain with local unconformity by bedded tuff, as much as 60 m (200 ft) thick, which is in turn overlain by the Bullfrog Member of the Crater Flat Tuff.

tuff at hill 5504 consists of a light-yellowish-gray ..elded basal zone of shards, several metres thick, grading upward to a brown densely welded zone, which locally includes a thin dark-gray vitrophyre less than 5 m (15 ft) thick. The upper 100 m (330 ft) becomes less welded with increasing crystallinity and is light purplish gray, mottled with red—the red coloration giving the name to Redrock Valley, which in turn is here reapplied to the tuff. Small light-colored pumice lenticles 1–2 cm long in the devitrified zone contain abundant tiny (0.2–1.0 mm) biotite and hornblende phenocrysts that aid in identification of the unit. Quartz is absent to very sparse and, where present, commonly cannot be seen with a hand lens. The uppermost part of the tuff locally reflects vapor-phase type crystallization (Smith, 1960b). The tuff has the zonation of a simple cooling unit.

Petrographically, the rock can be distinguished from all other ash-flow tuffs at the Nevada Test Site by the criteria shown in figure 5. It typically contains hornblende, like the other calc-alkalic tuffs and lavas of the Sleeping Butte center. The lower part has a plagioclase to alkali feldspar phenocryst ratio of about 3:1 and very little or no quartz. The upper part, in contrast, has about equal feldspar phenocrysts and sparse quartz. Phenocrysts seemingly increase slightly in the upper part, despite less compaction and welding. Small euhedral quartz microphenocrysts, commonly less than 0.5 mm and never exceeding 1.0 mm, are diagnostic of the unit; two thin sections examined from the lowermost part of the tuff were quartz-free, but all sections cut from the upper part contain quartz. The division between the upper and lower parts is based on petrography and has not been recognized in the field. The twofold division can be recognized in surface samples and also in drill core from the area northwest of Yucca Flat.

The K-Ar age of sanidine in the local basal vitrophyre of the Redrock Valley Tuff from the type locality at hill 5504 is 15.7 m.y., which is in good agreement with K-Ar ages of the overlying and underlying units (Marvin and others, 1970). This age is close to the onset of volcanism at the Timber Mountain–Oasis Valley caldera complex and postdates nearly all the volcanic activity in the Northern Nellis Bombing and Gunnery Range to the north (Ekren and others, 1971). The thermal remanent magnetization is reverse polarity (G. D. Bath, written commun., 1968). Two chemical analyses of the tuff, one of the lower part and the other of the upper part, were made (W. D. Quinlivan and P. W. Lipman, written commun., 1974); the silica contents of these rocks are shown graphically in figure 5.

CRATER FLAT TUFF AND INTERCALATED LAVA

The Crater Flat Tuff is here named from exposures around the edges of Crater Flat (fig. 4), which is designated the type area of the formation. The tuff consists of a lower member, the Bullfrog Member (new), and an upper member, the Prow Pass Member (new), and local, unnamed intercalated breccia, bedded tuff, and ash-flow tuff. Both members and the intercalated breccia are well exposed at the southeast end of an unnamed hogback at south side of Crater Flat which is designated the type locality of the Crater Flat Tuff (fig. 4). This is the only known section in which both members are largely glassy and virtually unaltered and, therefore, amendable to K-Ar age dating. The thickness at the type locality totals about 190 m (620 ft), of which the Bullfrog Member is 130 m (430 ft), intercalated breccia, 10 m (30 ft), and the Prow Pass Member, 50 m (160 ft).

The Crater Flat Tuff has been shown as "tuff of Crater Flat" on several U.S. Geological Survey 7½-minute quadrangle maps (fig. 2) covering the southern part of the Nevada Test Site (Christiansen and Lipman, 1965; Orkild and O'Connor, 1970; Poole, Elston, and Carr, 1965; Sargent and others, 1970). On the east side of the Wahmonie volcanic center (Poole, Elston, and Carr, 1965; Poole, Carr, and Elston, 1965) a local middle ash-flow tuff, similar to the underlying Bullfrog Member, is included with the formation.

A local intercalated rhyolite lava in the south wall of the Oasis Valley caldera segment (fig. 4) is not included in the Crater Flat Tuff, in accordance with prior practice by authors of reports on Nevada Test Site geology. This lava is described here because it has about the same phenocryst ratios as the underlying Bullfrog Member—suggestive of a common origin. The lava has been altered in most places along with the underlying member and cannot conveniently be mapped separately. It has been included with the Crater Flat Tuff on the map of the Timber Mountain caldera area (Byers and others, 1976).

Duplicate K-Ar ages on biotites from vitrophyre in the lower part of the Bullfrog Member are 14.0 and 13.0 m.y. For reasons previously discussed (Marvin and others, 1970, p. 2667), the 14.0-m.y. age is believed more reliable. The natural thermal remanent magnetism of both members of the Crater Flat Tuff is normal (G. D. Bath, written commun., 1965).

BULLFROG MEMBER

The Bullfrog Member, whose known distribution is shown in figure 4, is here named for the lower ash-flow sheet of the Crater Flat Tuff from exposures at Bullfrog Mountain (fig. 4). The type locality of the member is exposed on the mountain just north of the original Bullfrog mine, shown on the Bullfrog quadrangle (fig. 2) mapped by Cornwall and Kleinhampl (1964, pl. 4). These authors (1964, pl. 5, p. J10) described the member as cooling unit 2 of their Bullfrog Hills caldera and showed a composite thickness of 280 m (930 ft) in the Bullfrog Hills.

The Bullfrog Member is 130 m (430 ft) thick in the type locality of the Crater Flat Tuff at the south end of Crater Flat and is locally as much as 180 m (600 ft) thick in the northern part. Exposures of the member either are incomplete or were not mapped separately east of Crater Flat; therefore, maximum thicknesses are not known, but are probably as much as 150 m (500 ft) in paleovalleys. Thicknesses in Yucca Flat and in the Rainier Mesa area to the northwest do not exceed 120 m (400 ft). As the distal edges are approached, such as near the southwest corner of Lincoln County, the thickness of the unit ranges from 15 to 30 m (50 to 100 ft).

The unit is incompletely exposed south of Sleeping Butte (fig. 4), but probably the thickness does not exceed 60 m (200 ft). From drill hole UE20j to UE20f, just outside and inside the Silent Canyon caldera, respectively, the unit decreases slightly from 170 to 130 m (560-430 ft) in thickness (Orkild and others, 1969, section *A-A'*). The unit probably predates the formation of Silent Canyon caldera, for there is no great difference in thickness between the two holes inside and outside the caldera, and the unit has been downdropped 2,660 m (8,720 ft) to the east along later caldera faults (Orkild and others, 1969, section *A-A'*).

The Bullfrog Member probably originally covered a larger area than that indicated on figure 4 and may have extended into the Death Valley area west of the Grapevine Mountains and southwesterly under the Amargosa Desert. The northwestern extent under Sarcobatus Flat is also unknown. If an original area of 6,500 km^2 (2,500 mi^2), twice that of the Redrock Valley Tuff, were covered, a maximum of 1,000 km^3 (250 mi^3) may have originally been present.

The Bullfrog Member is commonly conformable on underlying bedded ash-fall tuff, which in turn separates the Bullfrog from the underlying Redrock Valley Tuff. In the Bullfrog Hills and on the eastern flank of the Grapevine Mountains (fig. 4), the member rests concordantly on bedded tuffaceous sandstone that overlies the Oligocene Titus Canyon Formation (Stock and Bode, 1935). At the type locality at Bullfrog Mountain, the member rests on cooling unit 1 of Cornwall and Kleinhampl (1964). To the east along the southern border of its known extent, the member rests on the rocks of Pavits Springs (Poole, Elston, and Carr, 1965; Poole, Carr, and Elston, 1965). The member is overlain at the type locality of the Crater Flat Tuff by a monolithologic breccia composed of fragments of the member. It is overlain by the lava flow that is petrographically similar to the member in the south wall of the Oasis Valley caldera segment (fig. 4). Elsewhere the Bullfrog Member is overlain by bedded tuff of the Crater Flat, which, in turn, is overlain by the Prow Pass Member. Locally on the east flank of the Wahmonie volcanic center, a middle ash-flow petrographically similar to the underlying Bullfrog Member intervenes between the members. In drill hole UE20j on Pahute Mesa, the Bullfrog Member is separated from the overlying peralkaline Tub Spring Member of the Belted Range Tuff (Noble, Sargent, and others, 1968; Orkild and others, 1969) by 51.8 m (170 ft) of bedded ash-fall tuff. In drill hole UE20f, lavas of peralkaline composition occur below the member, and the tuff of Tolicha Peak occurs above the member. In exposures just north of Redrock Valley and in drill cores in the Rainier Mesa area the Bullfrog Member occurs as a local nonwelded tuff at or near the top of tunnel bed 1 of the Indian Trail Formation (D. L. Hoover, oral commun., 1974).

In lithology and petrography the calc-alkalic Bullfrog Member of the Crater Flat Tuff is generally similar to the Redrock Valley Tuff but differs in containing significant euhedral quartz phenocrysts (fig. 5) as long as 2.5 mm. The member has a feldspar compositional zonation with plagioclase significantly in excess of alkali feldspar in the lower part and feldspars subequal in the upper part. The common biotite flakes in small (1-3 cm) white pumice lenticles are an identifying criterion which, along with readily visible quartz phenocrysts, serve to distinguish the member from the Redrock Valley Tuff. The ash-flow sheet is brown and glassy in the lower part at the type locality of the Crater Flat Formation at the south side of Crater Flat, but elsewhere the Bullfrog Member is light yellowish gray, slightly mottled with yellow and pale reddish brown and microcrystalline from base to top. The sheet, where the top

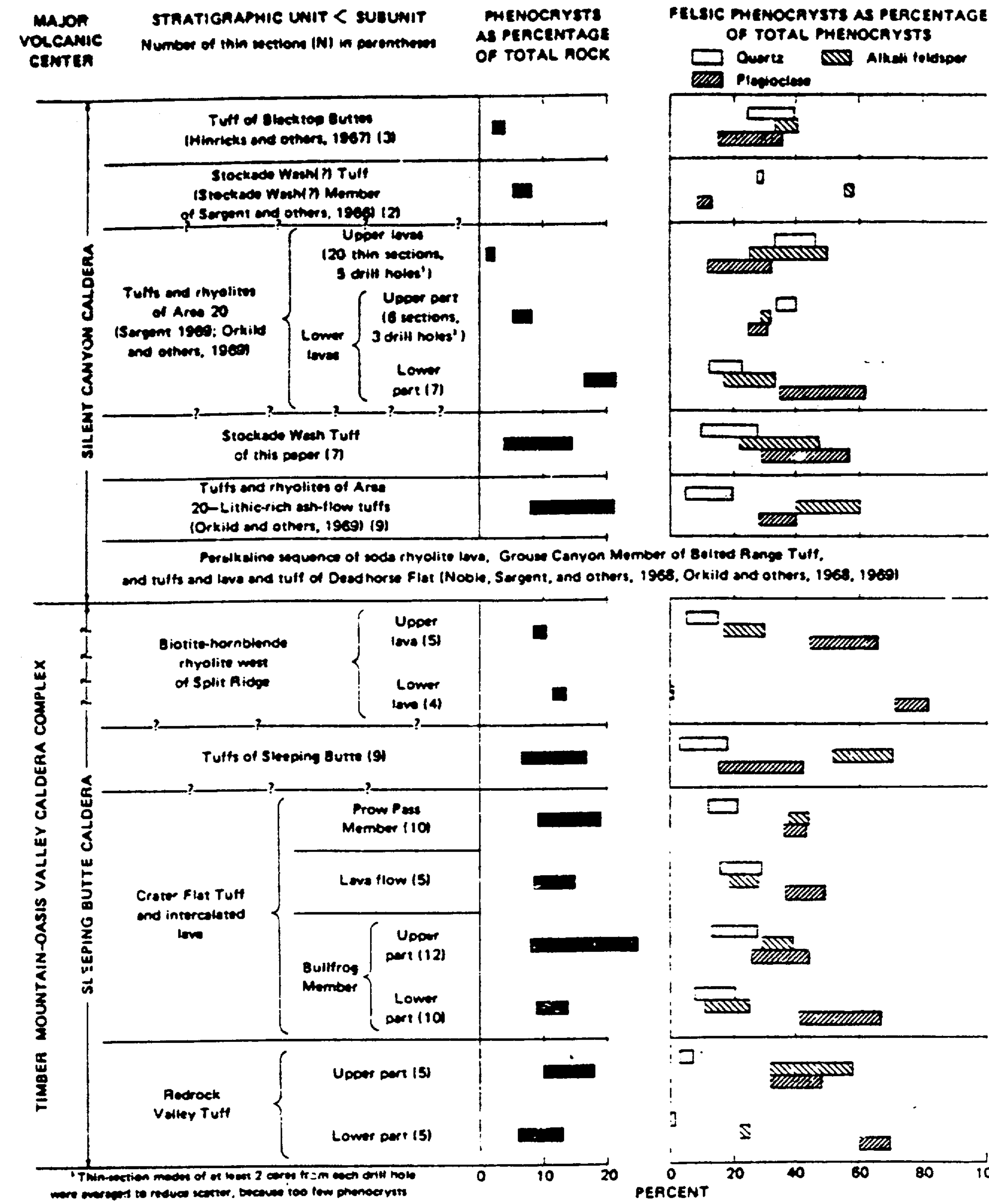


FIGURE 5.—Modal and silica ranges of Redrock Valley, Crater Flat, and Stockade Wash Tuffs and petrologically related lavas in general

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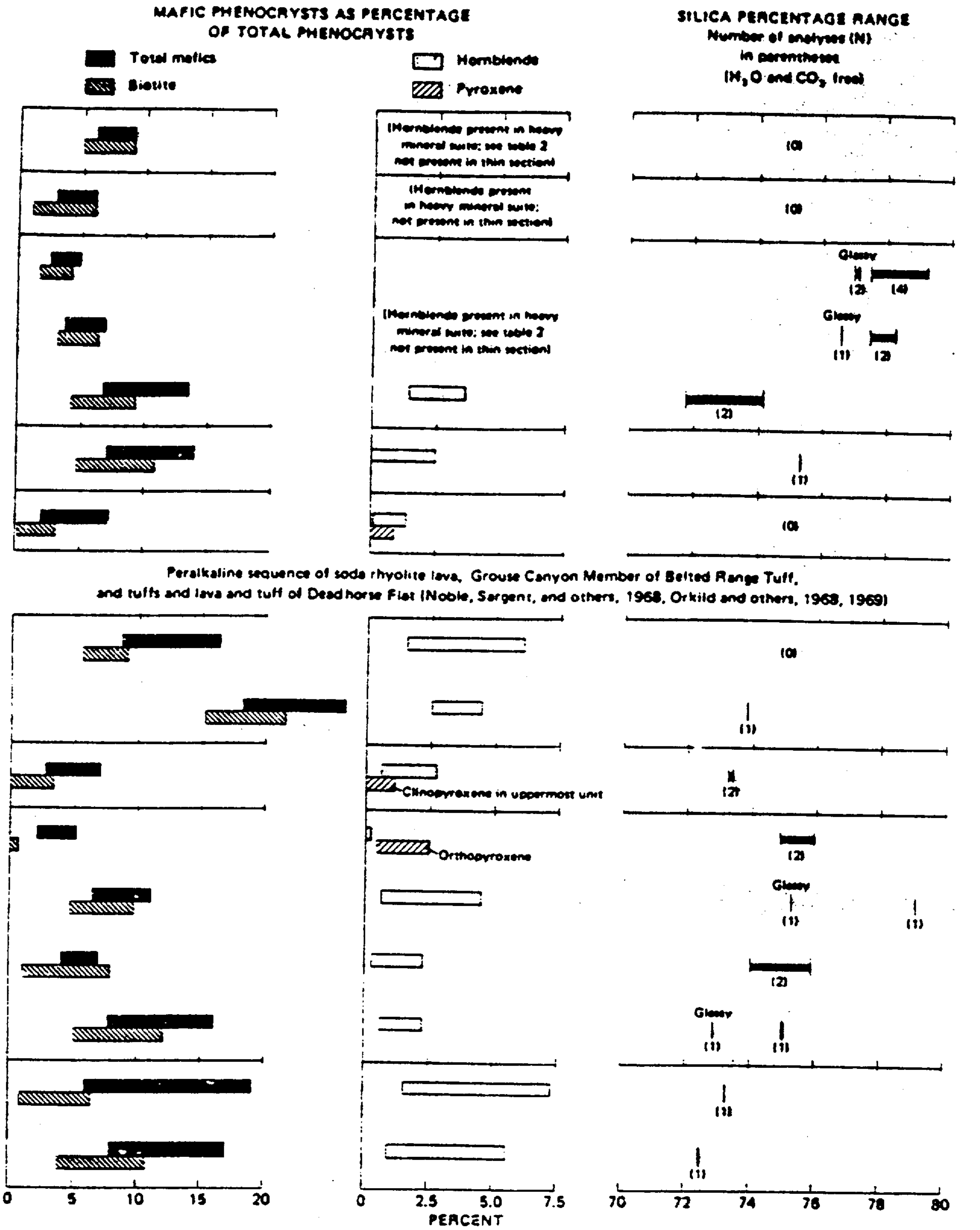


ler of stratigraphic succession. Units with queried boundaries may be in reverse stratigraphic order from that shown or may intertongue.

is not eroded, has an upper part that contains crystals of the vapor-phase zone in pumice. In the Bullfrog Hills, the member is silicified and locally mineralized with sulfides and gold (Cornwall and Kleinhampl, 1964, p. J22) and is moderately welded. In the Yucca Flat area, northern Frenchman Flat, and in drill hole UE20j (fig. 1), the member is nonwelded to slightly welded and the original glass is now altered to zeolites.

In drill hole UE20f (fig. 4) where the tuff member was penetrated between depths of 3,500 and 3,650 m (11,500 and 12,000 ft), the biotite has been completely replaced by chlorite, and the feldspars have been partly replaced by sericite. All these differing facies and degrees of alteration of the ash-flow sheet might cause great difficulty in correlation were it not for the lateral persistence of a unique phenocryst assortment (fig. 5), general stratigraphic position, and certain lithologic features, such as small, flattened biotite-bearing pumice lenticles not destroyed by alteration.

The petrochemistry (W. D. Quinlivan and P. W. Lipman, written commun., 1974) of the Bullfrog Member is similar to that of the underlying Redrock Valley Tuff (fig. 5) in that the lower part of the ash-flow sheet is slightly more mafic and less silicic than the upper part. Although sampling has been limited, field observations suggest no sharp break between the upper and lower parts; the subdivision is arbitrary and based on petrography.

INTERCALATED LAVA FLOW

A brownish-gray fluidal lava flow overlying the Bullfrog Member but not part of the Crater Flat Tuff is exposed in fault blocks in the south wall of the Oasis Valley caldera segment (fig. 4). The lava pinches out a short distance south of the wall, for exposures of both members of the Crater Flat Tuff at Prow Pass and at the north end of Crater Flat include only intervening bedded tuff. A downfaulted portion of the lava is doubtless buried beneath younger volcanic rocks in the Oasis Valley caldera segment. The exposed part of the lava flow does not exceed 60 m (200 ft) in thickness.

The Prow Pass Member rests directly on the lava, but as much as 15 m (50 ft) of bedded tuff separates the lava from the underlying Bullfrog Member.

The lava superficially resembles the underlying Bullfrog Member, but its fluidal flow banding identifies it as a lava flow. The lower part locally includes a vitrophyre, whereas the brownish-gray uppermost part contains spheroidal white pumice with abundant fine biotite phenocrysts resembling the tuff. The thin-section modes of three specimens of the lava are well within the range of 22 modes of the Bullfrog Member (fig. 5). Two chemical analyses of the lava (W. D. Quinlivan and P. W. Lipman, written commun., 1974) indicate that the devitrified specimen is several percent higher in SiO_2 content than is the specimen of the basal vitrophyre (fig. 5).

PROW PASS MEMBER

The Prow Pass Member of the Crater Flat Tuff is here named after Prow Pass, the type locality, at the north end of Yucca Mountain (fig. 4). At the type locality at Prow Pass, 15.2 m (50 ft) of devitrified welded tuff constitutes the upper cooling unit of the Crater Flat. The member is slightly thicker and more densely welded in the northern part of the Crater Flat area than it is in the southern part. At the type locality of the Crater Flat Tuff (fig. 4), the member is 50 m (160 ft) thick, but is partly glassy and only slightly welded. Near the eastern and southeastern edges of its extent, the Prow Pass Member is about 15 m (50 ft) thick and, like the Bullfrog Member, it is nonwelded and zeolitized. The member has not been recognized and probably is not present outside the Timber Mountain-Oasis Valley caldera complex north of the area shown in figure 4. The estimated extracaldera complex volume of the unit is only about 30 km³ (8 mi³), but the member may be several times thicker within the complex where an equal or greater volume could be present.

The Prow Pass Member underlies all the constructional lavas of the calcic Wahmonie-Salyer volcanic center (Poole, Elston, and Carr, 1965; Poole, Carr, and Elston, 1965; Noble and others, 1965) and the rhyolite lavas of the Calico Hills (Christiansen and Lipman, 19[illegible]). The age relations to the post-Crater Flat tuffs on the west rim of Sleeping Butte caldera segment are unknown from stratigraphic relations but the member may be older, on the basis of an inferred upward increase of phenocrystic alkali feldspar (fig. 5), typical of the later volcanic suites. The age relations to the peralkaline Tub Spring Member of the Belted Range Tuff (Sargent and others, 1965) are uncertain, but the member underlies a phenocryst-poor green peralkaline ash-fall tuff that underlies the Grouse Canyon Member of the Belted Range Tuff (fig. 5).

The calc-alkalic Prow Pass Member has some general similarities in lithology to the Bullfrog Member, but it is thinner, generally less welded, and practically devoid of biotite. The unit is generally light gray, grayish pink, or moderate orange pink where devitrified, but is light brown where glassy at the type locality of the Crater Flat. Petrographically, it is a unique unit of all the silicic tuffs of the region in that it contains orthopyroxene as the dominant mafic phenocryst (fig. 5) and, in the extreme, almost lacy resorption of the quartz phenocrysts. No other ash-flow sheet in the region could be mistaken for this unit. However, orthopyroxene is preserved only in the glassy upper and lower parts of the cooling unit at the type locality of the Crater Flat Tuff; elsewhere the unit is devitrified and only smudgy opaque oxide pseudomorphs remain. The silica contents of two devitrified specimens are shown graphically in figure 5.

TUFFS OF SLEEPING BUTTE AND THEIR RELATION TO CALDERA WALL

Rocks under this heading comprise a sequence of three similar ash-flow tuff cooling units occupying the west rim of the Sleeping Butte caldera in the vicinity of Sleeping Butte (fig. 4). The caldera rim is delineated for several miles by the axis of an easterly dipping monocline in the tuff. The tuffs of Sleeping Butte are slightly more than 300 m (1,000 ft) thick at Sleeping Butte, where the upper cooling unit is well exposed. Along the west rim of the caldera the monocline exposes 150–240 m (500–800 ft) of the tuffs. The outcrop area shown in figure 4 is delimited by the onlap of younger rocks.

The monocline dips easterly under the peralkaline Grouse Canyon Member of the Belted Range Tuff and younger rocks, which fill the Sleeping Butte caldera segment. Near the southern end of the exposure, relatively unfractured but locally vertically dipping tuffs of Sleeping Butte probably onlap the highly fractured caldera wall consisting of the Redrock Valley Tuff and the Bullfrog Member of the Crater Flat Tuff, although the contact is not exposed. The local vertical attitude in the onlapping tuffs of Sleeping Butte strikes north, parallel to the inferred caldera wall, and is typical of the most easterly exposure. The steep initial dip of the tuffs probably occurred as they were compacted and plastered against the Sleeping Butte caldera wall.

The inferred younger age relation of the tuffs of Sleeping Butte to the Prow Pass Member of the Crater Flat Tuff is suggested partly by the close stratigraphic succession of the units of the Crater Flat Tuff, and partly by the increase of alkali feldspar upward. The unfractured nature of the tuffs with respect to the highly fractured Bullfrog Member also indicates their younger age, probably as postcaldera tuffs draped over a wall composed of the Bullfrog Member and older rocks.

The three ash-flow cooling units of the tuffs include a lower nonwelded to partly welded, phenocryst-poor shard tuff (not shown in figure 5), a middle purple welded tuff that contains fluidal flow banding where it dips inward (easterly) into the caldera, and an upper tuff, mainly exposed around Sleeping Butte. All the tuffs of Sleeping Butte are mostly light purplish gray, light brown, and microcrystalline; basal vitrophyres are practically nonexistent and the rocks are commonly mildly silicified and sericitized to the extent that former plagioclase phenocrysts are completely gone. Xenoliths are common and consist mainly of altered silicic volcanic rock and less common pilotaxitic intermediate and mafic lava. The fluidal flow banding of the middle unit, locally vertical, occurs only at its eastern margin where it dips into the inferred Sleeping Butte caldera.

The thin-section modes of the middle and upper tuffs of Sleeping Butte are pooled graphically in figure 5. The lower shard-rich tuff is phenocryst-poor (2 to 5 percent phenocrysts) somewhat altered, and therefore not pooled with the overlying units. Its phenocryst percentages, based on only two sections, are roughly similar to those of the middle and upper unit; the chemical analysis (W. D. Quinlivan and P. W. Lipman, written commun., 1974) indicates a more silicic rock at 75.1 percent SiO_2 (water-free) than the two phenocryst-rich specimens of the middle and upper units (fig. 5). The middle and upper units are similar in modal petrography except for sparse pigeonitic(?) clinopyroxene (low $2V$, slightly pleochroic in pale green and yellow) in addition to hornblende in the upper unit. This is the oldest unit containing significant clinopyroxene phenocrysts. The presence of pigeonitic (low Ca) clinopyroxene in the highest stratigraphic unit of the tuffs of Sleeping Butte is analogous to the occurrence of orthopyroxene (low Ca) in the Prow Pass Member, the uppermost cooling unit of the Crater Flat Tuff.

High potassium (W. D. Quinlivan and P. W. Lipman, written commun., 1974) in all three tuffs is due partly to very minor sericite replacing plagioclase, but the dominantly alkali feldspar phenocrysts indicate that most of the potassium is primary. Therefore, these youngest rocks of the Sleeping Butte caldera center approach the alkali-calcic composition of the overlying Paintbrush and Timber Mountains Tuffs and may be products of a late alkali enrichment in the upper part of the Sleeping Butte magma chamber.

TUFF OF TOLICHA PEAK

The tuff of Tolicha Peak (Noble and Christiansen, 1968; Rogers and others, 1968) is a local phenocryst-poor densely welded shard tuff, about 60 m (200 ft) thick, that occurs above the Bullfrog Member of the Crater Flat Tuff in drill hole UE20f (fig. 4; Orkild and others, 1969, cross section *A–A'*). The unit crops out in the north half of the Black Mountain 15-minute quadrangle (fig. 2) and in the southwest quarter of the quadrangle in the vicinity of Quartz Mountain and Tolicha Peak (fig. 1); it was penetrated in a drill hole in eastern Yucca Flat. The unit is distinctive lithologically and also petrographically in that it contains sparse quartz and plagioclase dominant over alkali feldspar. The tuff may be related to the Sleeping Butte caldera (Christiansen and others, 1976); however, E. B. Ekren (oral commun., 1974; Ekren and others, 1971, p. 60) has evidence suggesting a source from the north in the Mount Helen area (fig. 4).

BIOTITE-HORNBLENDE RHYOLITE LAVAS WEST OF SPLIT RIDGE

Two calc-alkalic rhyolite lava flows and underlying petrographically similar ash-flow and ash-fall tuffs intertongue with peralkaline members of the Belted Range

Tuff and related lavas (Sargent and others, 1965; Noble, Sargent, and others, 1968) in the triangular salient between Silent Canyon caldera, Timber Mountain caldera, and the peralkaline lava pile of Split Ridge (fig. 4). These rocks occupy approximately the same stratigraphic position as the tuffs of Sleeping Butte; they also contain hornblende but are petrographically more mafic like the Redrock Valley Tuff (fig. 5). They are therefore generally similar to other calc-alkalic rocks grouped under Sleeping Butte caldera and are included here for convenience. Magnetic polarity determinations by G. D. Bath (written commun., 1965) indicate a reverse orientation in these rocks in contrast to normal remanent magnetization of the enclosing peralkaline rocks.

The two lavas and underlying tuffs were called quartz latite flows and quartz latite tuff on the geologic map of the Ammonia Tanks quadrangle (fig. 2; Hinrichs and others, 1967); however, the one analyzed vitrophyre of the lower, more mafic, plagioclase-rich lava is chemically rather silicic at 73.9 percent SiO_2 (fig. 5), and total alkalis are 7 percent (W. D. Quinlivan and P. W. Lipman, written commun., 1974); hence these rocks are called rhyolite in this report and on the geologic map of the Timber Mountain area (Byers and others, 1976). Hinrichs, Krushensky, and Luft (1967) show a maximum thickness of 364 m (1,195 ft), comprising 114 m (375 ft) of underlying tuff, 174 m (570 ft) of lower lava, and 76 m (250 ft) of upper lava. The lower flow is a thick lenticular exposure in a short canyon tributary to Timber Mountain caldera; the overlying and underlying units are more stratiform and do not pinch out within the exposed area.

The biotite-hornblende tuff-lava sequence west of Split Ridge is transected by green, peralkaline feeder dikes and vent breccias of the rhyolite complex of Split Ridge and is also overlain by greenish-gray peralkaline bedded tuff-breccia under the rhyolite lava of Split Ridge, which in turn underlies the Grouse Canyon, the upper member of the Belted Range Tuff. The sequence overlies greenish-yellow peralkaline bedded tuff that in turn overlies the Tub Spring, the lower member of the Belted Range Tuff.

The basal tuffs include two, possibly three, nonwelded ash-flow tuffs as much as 23 m (75 ft) thick, and intercalated bedded tuff. They are yellowish gray, weather lighter gray, and are typical of calc-alkalic zeolitized tuff stratigraphically between the Grouse Canyon Member and the Crater Flat Tuff in the area between Yucca Flat and Timber Mountain caldera (fig. 4). The phenocryst mineralogy of these basal tuffs is generally similar to that of the overlying biotite-hornblende rhyolite lavas.

The lavas superficially resemble other calc-alkalic rhyolite lavas associated with the Timber Mountain-Oasis Valley caldera complex. Both lavas have a glassy breccia envelope, a dark basal vitrophyre, and a purplish-gray fluidal flow-banded middle part with conspicuous small phenocrysts, less than 2 mm, of feldspar, biotite, and hornblende (fig. 5). The occurrence of a few phenocrysts of sphene in every thin section of these lavas contrasts with the sporadic occurrence of sphene in other volcanic rocks of the Sleeping Butte caldera.

PERALKALINE ROCKS OF SILENT CANYON CALDERA

A complete description of the peralkaline rocks related to the Silent Canyon caldera center is beyond the scope of this paper; these rocks are described elsewhere (Sargent and others, 1965; Noble, Sargent, and others, 1968; Orkild and others, 1968; Orkild and others, 1969; Sargent, 1969; Noble and others, 1969; Noble, 1970; and Christiansen and others, 1976). These unique rocks, however, provide an extremely helpful datum for stratigraphic assignments of the rocks of the Timber Mountain-Oasis Valley caldera complex and, therefore, are mentioned briefly here.

The comenditic Tub Spring and Grouse Canyon Members constitute, respectively, the lower and upper ash-flow sheets of the Belted Range Tuff (Sargent and others, 1965). Many peralkaline lava flows, including the rhyolite lava of Split Ridge, are genetically related to these sheets and occur within and around the Silent Canyon caldera center (Noble, Sargent, and others, 1968). The Tub Spring Member overlies the Crater Flat Tuff in drill hole UE20j (fig. 4), and the exposed uppermost part of the Tub Spring underlies the calc-alkalic biotite-hornblende rhyolitic rocks west of Split Ridge. The Grouse Canyon Member is much more widespread, covering about 8,000 km² (3,000 mi²) (Noble, Sargent, and others, 1968, p. 67), and represents the peak of peralkaline igneous activity. The maximum extracaldera thickness is about 90 m (300 ft), and the original volume of the member is about 200 km³ (50 mi³). The Grouse Canyon and related peralkaline rocks (fig. 5) separate the underlying calc-alkalic rocks of the Sleeping Butte caldera from overlying similar calc-alkalic effusives that were erupted from the Area 20 center late in the development of Silent Canyon caldera.

STOCKADE WASH TUFF AND RELATED CALC-ALKALIC ROCKS ASSOCIATED WITH SILENT CANYON CALDERA

The Stockade Wash Member was first named by Hinrichs and Orkild (1961, p. D98) as a unit of the Oak Spring Formation from the thick exposure in Stockade Wash south of Rainier Mesa (fig. 6). The member was mapped in Rainier Mesa (Gibbons and others, 1963) and Tippipah Spring quadrangles (fig. 2; Orkild, 1963). Poole and McKeown (1962, p. C61) raised the rank of the Oak Spring to group status and divided it into the Indian Trail and Piapi Canyon Formations. Their Piapi Canyon included, in ascending order, the Survey Butte, Stockade Wash, Topopah Spring, Tiva Canyon, and Rainier Mesa

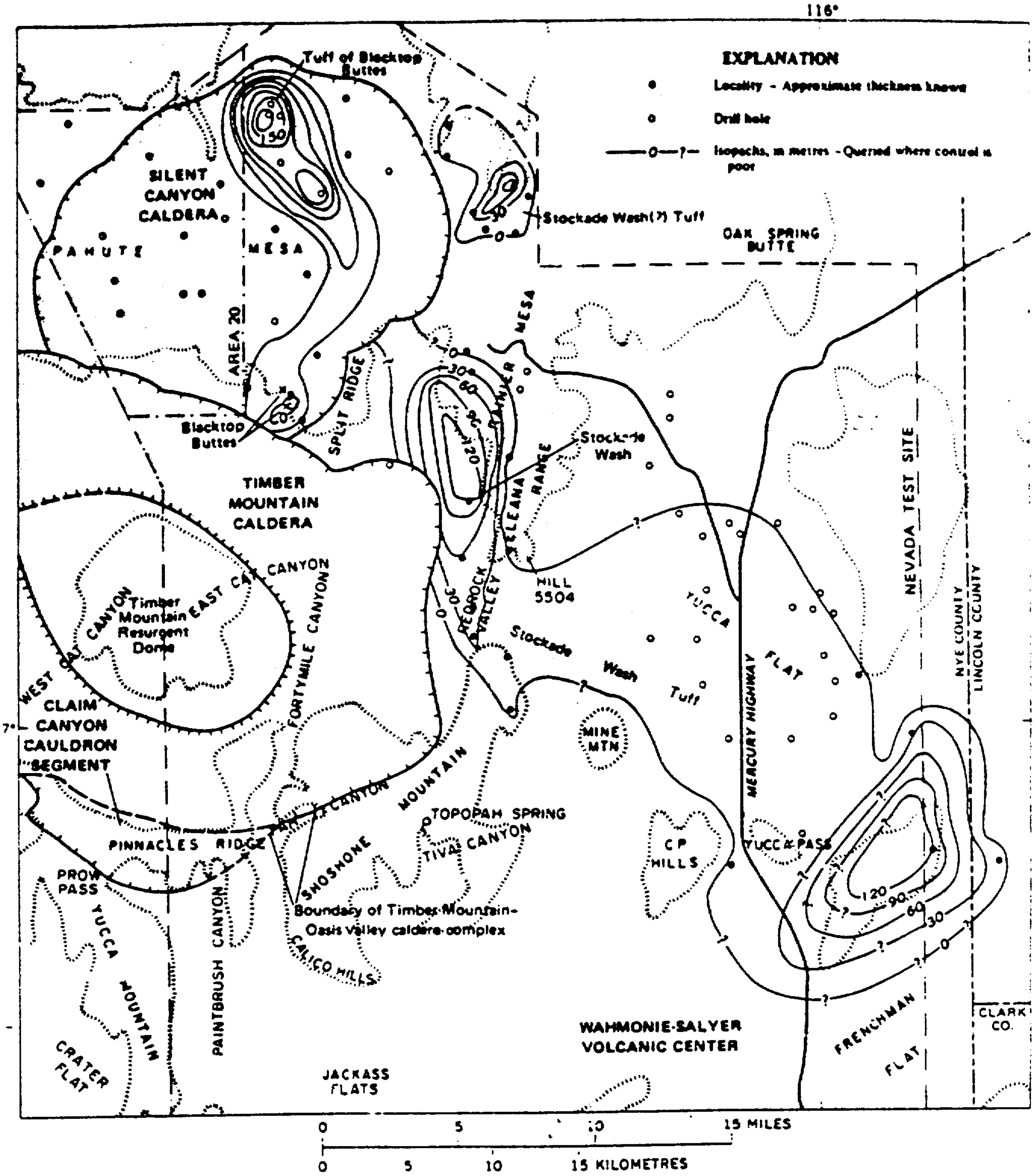
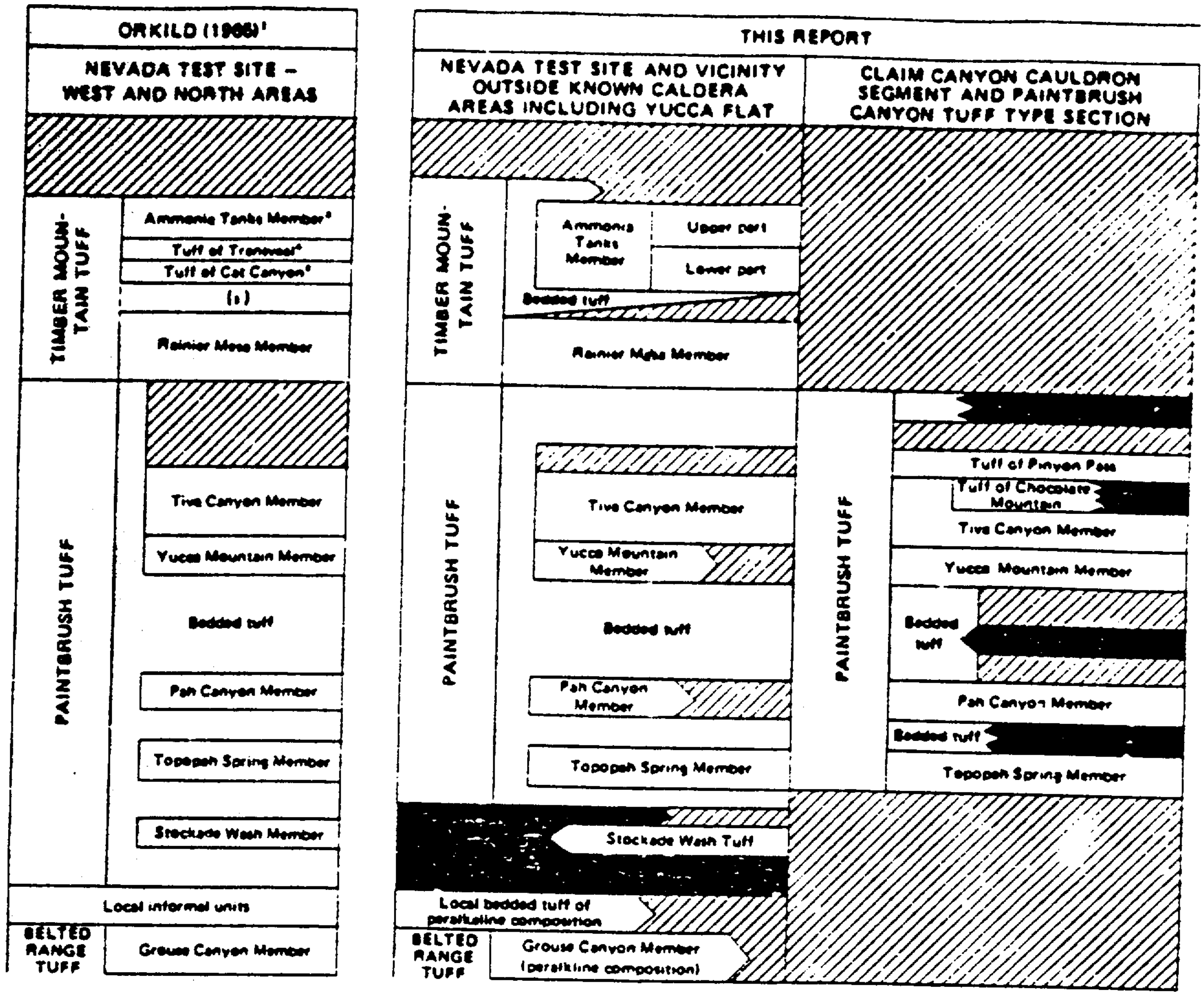


FIGURE 6.—Isopachs of Stockade Wash Tuff, Stockade Wash(?) Tuff, and tuff of Blacktop Buttes in relation to Silent Canyon caldera.

Members. Later Orkild (1965) abandoned the Oak Spring Group and raised the Piapi Canyon to group, consisting of the Paintbrush and Timber Mountain Tuffs. His subdivision of these formations, which included the Stockade Wash Member at the base of the Paintbrush, is shown in the left column of figure 7.



[1]Geometry of Orkild's (1966) diagram slightly altered in an attempt to make it fit new information presented here and still retain the stratigraphic relations in his diagram.

[2]Noble, Krushensky, McKay, and Ege (1967).

[3]Hinrichs, Krushensky, and Luft (1967). The Pah Canyon Member shown in their section A–A' is a local unit of the Paintbrush Tuff that seemingly grades upward into the overlying pyroxene-bearing rhyolite lava. See text.

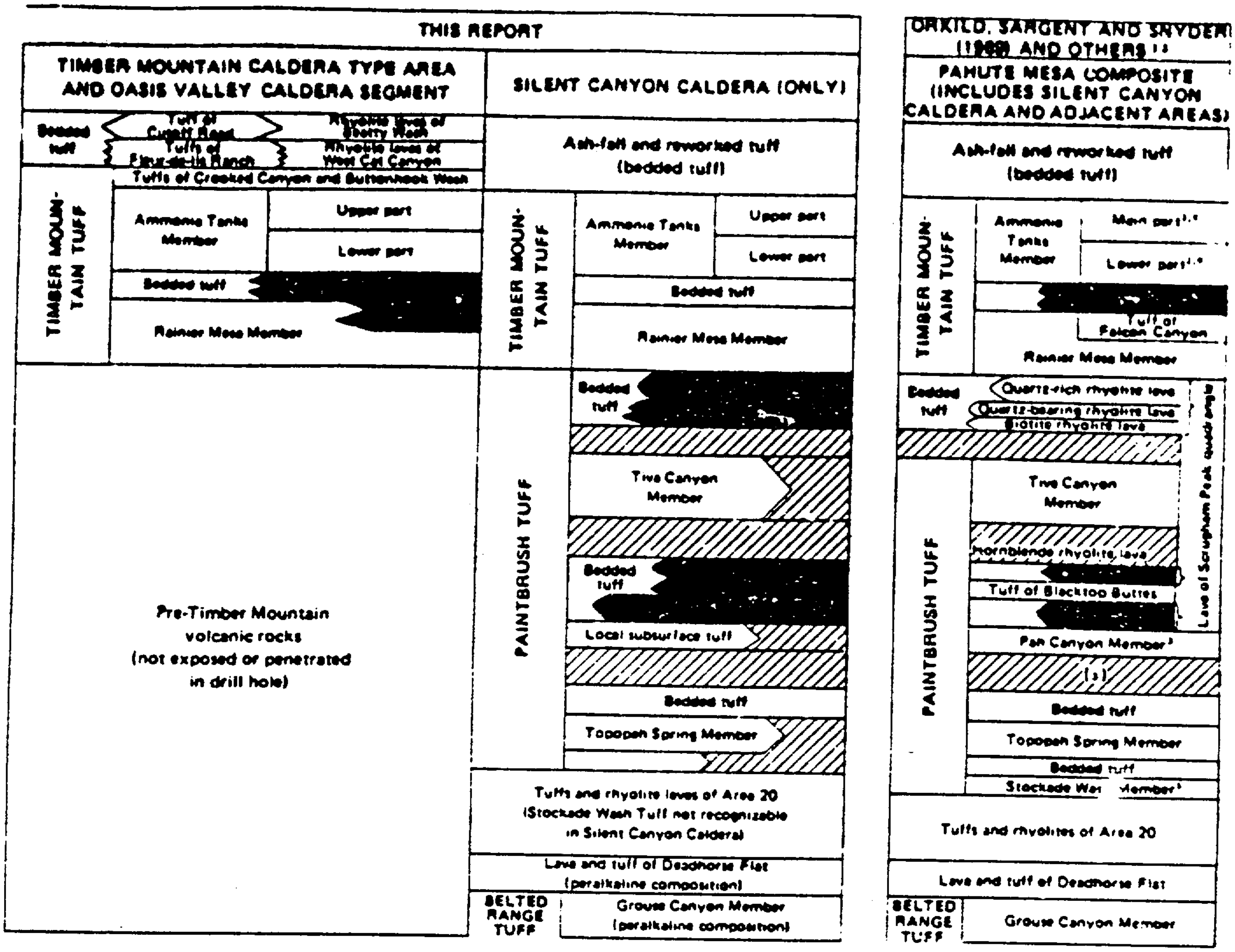
[4]Ammonia Tanks Member as mapped by Orkild, Sargent, and Snyder (1969) in most places around the rim of Timber Mountain caldera is the upper part of the Ammonia Tanks of this report and the main part as mapped by Noble, Krushensky, McKay, and Ege (1967). The tuff of Transvaal of Orkild (1966) is equivalent to all the lower part of the Ammonia Tanks Member as mapped by Noble, Krushensky, McKay, and Ege (1967). The intracaldera tuff of Cat Canyon as mapped by Carr and Quinlivan (1968) is equivalent to the entire Ammonia Tanks of this report and is a single compound cooling unit. See text.

[5]The former Stockade Wash Member of the Paintbrush Tuff was placed above the tuffs and rhyolites of Area 20 by Orkild, Sargent, and Snyder (1969) but is now known to be stratigraphically equivalent to some part, possibly near the middle, of the tuffs and rhyolites of Area 20.

FIGURE 7 (above and right).—Stratigraphic relations and revisions of Stockade Wash, Paintbrush, and Timber Mountain Tuffs, Timber Mountain caldera and vicinity. Dark-shaded units intertongue with these named tuffs but are not part of them. Diagonal ruling indicates unit is not present; light shading, bedded tuff.

The Stockade Wash Member is herein removed as the basal unit of the Paintbrush Tuff and raised to formational rank (second column, fig. 7) because it is lithologically and petrologically unlike the ash-flow tuff units of the Paintbrush and appears more closely related to the calc-alkalic tuffs and rhyolite lavas of Area 20 in Silent Canyon caldera. The areal distribution of the Stockade Wash Tuff and closely related units is shown in figure 6.

The tuff reaches its maximum thickness of slightly more than 120 m (400 ft) along the west side of Rainier Mesa and also in the low hills north of Frenchman Flat (fig. 6) where Hinrichs and McKay (1965) mapped the unit as the Stockade Wash(?) Member. Subsequent field and petrographic work have established the identity of their unit in the northern Frenchman Flat area with that at the type section. The volume of the Stockade Wash Tuff is



probably between 20 and 40 km³ (5 and 10 mi³), depending on its largely unknown thickness and extent under Yucca and Frenchman Flats.

The areal distribution pattern of the Stockade Wash, trending generally southeast from Silent Canyon caldera, is similar to that of the peralkaline ash fall of the Belted Range Tuff (Noble and others, 1968, fig. 2), which came from Silent Canyon caldera, and is unlike the distribution patterns of members of the Paintbrush Tuff (figs. 8, 9) which originated in the southern or southwestern part of the Timber Mountain-Oasis Valley caldera complex. The closest exposure of the Stockade Wash Tuff to the type section of the Paintbrush is about 15 miles.

The Stockade Wash Tuff, where present in the Rainier Mesa and Yucca Flat areas, rests on zeolitic tuffs of the tuffs and rhyolite lavas of Area 20 but has not been recognized in drill holes inside Silent Canyon caldera (figs. 6 and 7). The lithic-rich ash-flow tuff in the lower part of the tuffs and rhyolite lavas of Area 20 within Silent Canyon caldera (Orkild and others, 1969) has also been recognized in several drill holes in Yucca Flat where it reaches a maximum thickness of 64 m (210 ft). The lithic-rich ash-flow tuff is separated from the overlying Stockade Wash by less than 10 m (35 ft) of zeolitic lithic-rich bedded tuff and rests on the Grouse Canyon Member of the Belted Range Tuff. The Stockade Wash Tuff is overlain by quartz-free friable glassy bedded tuff of the Paintbrush Tuff (Orkild, 1965), although, locally, a few metres (10 ft) of zeolitic lithic-rich bedded tuff occurs between the Paintbrush and the Stockade Wash. The best correlation of the Stockade Wash, based on petrography, is with the lower part of the lower rhyolite lava of the tuffs and rhyolites of Area 20 (see fig. 5), analogous to the relation of the Bullfrog Member of the Crater Flat Tuff with the petrographically similar lava (fig. 5). The Stockade Wash Tuff was probably erupted from the same magma as the lower lavas just before, in between, or just after the sequence of several lower rhyolite lavas of the tuffs and rhyolites of Area 20, which underlie the Paintbrush Tuff (fig. 7; Orkild and others, 1969). Therefore, where zeolitic quartz-bearing lithic-rich tuff are present beneath or just above the Stockade Wash, they are assigned to the tuffs and rhyolite lavas of Area 20, rather than to the Paintbrush Tuff (fig. 7).

The Stockade Wash Tuff is a simple cooling unit of massive nonwelded to partly welded ash-flow tuff having 4-9 percent of small phenocrysts generally less than 1 mm in length. It is characterized in the field by randomly oriented orange pumice fragments that average half an inch in length in a pale-yellowish-gray to light-yellowish-brown matrix. Locally the tuff is zeolitized at the base (Hinrichs and Orkild, 1961, p. D98; Gibbons and others, 1963). Despite its partly welded character, the Stockade Wash Tuff is a cliff-former and locally south of Stockade Wash contains rosettes of closely spaced polygonal joints possibly localized by fumaroles during cooling.

The Stockade Wash Tuff lithologically and mineralogically resembles two local massive nonwelded to very slightly welded simple cooling units, one of which is found outside the Silent Canyon caldera on the east and the other within the caldera (fig. 6). The one east of Silent Canyon caldera was mapped as Stockade Wash(?) Member of the Paintbrush Tuff in Quartet Dome quadrangle (fig. 2; Sargent and others, 1966). This cooling unit is likewise raised in rank to Stockade Wash(?) Tuff. The other cooling unit that resembles the Stockade Wash is the tuff of Blacktop Buttes (cols. 5 and 6, fig. 7; Hinrichs and others, 1967; Orkild and others, 1969), which is entirely confined within the Silent Canyon caldera (fig. 6). This tuff intertongues with the Paintbrush Tuff (as restricted in this paper) and was mapped with the Paintbrush on two geologic maps (Hinrichs and others, 1967; Orkild and others, 1969). Because of its lithologic similarity to the Stockade Wash, however, this tuff is herein regarded as local informal unit separate from the Paintbrush.

The Stockade Wash and Stockade Wash(?) Tuffs and the tuff of Blacktop Buttes are all characterized by sparse to abundant dark-greenish-gray dense devitrified xenoliths of peralkaline volcanic rock. These xenoliths closely resemble the peralkaline rocks, including the devitrified, microcrystalline facies of the rhyolite of Split Ridge and the Grouse Canyon Member of the Belted Range Tuff from the floor and the rim of Silent Canyon caldera. We therefore infer that these units were extruded from vents inside or on the rim of Silent Canyon caldera.

Average modal analyses of the Stockade Wash Tuff, Stockade Wash(?) Tuff, and tuff of Blacktop Buttes are compared in figure 5 with the lavas of the tuffs and rhyolites of Area 20; the intracaldera lavas are arbitrarily placed together. The modes suggest that the Stockade Wash and Stockade Wash (?) Tuffs each may generally correlate with the lower and the upper lavas, respectively, of the tuffs and rhyolites of Area 20. The Stockade Wash(?) Tuff, therefore, probably slightly postdates the type Stockade Wash and is a separate cooling unit. The tuff of Blacktop Buttes is known to be the youngest, for it postdates all the lavas of Area 20 (Orkild and others, 1969) and intertongues with two lavas related to the Paintbrush Tuff (cols. 5 and 6, fig. 7). In contrast with thin-section modes of Paintbrush Tuff units, the Stockade Wash and related tuffs contain common to abundant quartz and no clinopyroxene, although clinopyroxene has been found as a minor constituent of heavy-mineral separates.

Percentages of nonmagnetic heavy mineral separates from the Stockade Wash Tuff and probable related calc-alkalic units associated with the Silent Canyon caldera are compared with those separated from some units of the Paintbrush Tuff in table 2. The tuffs and rhyolite lavas of Area 20, the Stockade Wash Tuff, the Stockade Wash(?) Tuff, and the tuff of Blacktop Buttes are all characterized by a high allanite/sphene ratio and very low content of augite in contrast to alkali-calcic tuff units of the Paintbrush. In the Topopah Spring Member, however, the paucity of both allanite and sphene makes the ratio insignificant for comparison. None of the three Paintbrush units contain orthopyroxene in the heavy mineral assemblage, but the Stockade Wash Tuff and tuff of Blacktop Buttes each contain 1 percent. The trace amounts of aegirine-augite in the tuffs and rhyolite lavas of Area 20, as well as in the Stockade Wash (?) Tuff and in the tuff of Blacktop Buttes, may have been derived from abundant peralkaline xenoliths.

Chemical analyses of the lavas of Area 20 and the Stockade Wash Tuff were made (W. D. Quinlivan and P. W. Lipman, written commun., 1974); silica percentages of glass and devitrified rocks are plotted in figure 5. The lavas of the tuffs and rhyolites of Area 20 become progressively more silicic upward. The devitrified specimens are relatively enriched in silica with respect to the glassy specimens.

In summary, the Stockade Wash and the tuff of Blacktop Buttes are removed from the Paintbrush Tuff and from the Piapi Canyon Group. The Stockade Wash is raised in rank to a separate tuff formation, because it is lithologically and petrographically unlike any units in the Paintbrush Tuff but does show lithologic and petrographic affinities to late effusives occurring entirely within the Silent Canyon caldera. The Stockade Wash(?) Member of Sargent, Luft, Gibbons, and Hoover (1966), which occurs just east of and outside the Silent Canyon caldera, is also raised in rank but is retained as a queried unit because its petrographic features suggest that it correlates with a slightly higher part of the intracaldera sequence. The tuff of Blacktop Buttes (Hinrichs and others, 1967; Orkild and others, 1968), the youngest ash flow entirely confined to the Silent Canyon caldera, is regarded as an informal unit not assigned to a formally named formation.

TABLE 2.—*Nonmagnetic heavy minerals of Paintbrush and Stockade Wash Tuffs and related tuffs and lavas in order of stratigraphic succession*

[Stockade Wash Tuff and related units in italic type; r, mineral rare]

Unit and subunit (number of specimens)	Volume percent of total heavy minerals										
	Biotite	Augite	Aegirine augite	Clinohypersthene	Hornblende	Sphene	Allanite (not including perrierite(?))	Zircon	Apatite	Garnet, possibly spinel	Allanite: sphene ratio
Paintbrush Tuff: Tiva Canyon Member: Quartz latite (2)	19	31	0	0	9	18	12	9	1.3	0	0.7
Tuff of Blacktop Buttes (1)	*76*	*2.6*	*r*	*1.0*	*0.4*	*1.2*	*12*	*6*	*0*	*0*	*10*
Paintbrush Tuff: Local unit in hole UE19f (1)	57	6	0	0	0	24	8	6	0.8	0	0.3
Paintbrush Tuff: Topopah Spring Member: Quartz latite (1)	80	18	0	0	0	0	0.8	0.4	0	0	([1])
Stockade Wash(?) Tuff (1)	[2]*29*	*1.6*	*r*	*0*	*59*	*0.5*	*6.0*	*2.2*	*1.0*	*r*	*10*
Stockade Wash Tuff (1)	*72*	*0.4*	*0*	*1.0*	*18*	*0.2*	*3.4*	*6*	*2.2*	*0*	*17*
Rhyolite lavas of Area 20 (14)	*79*	*0.1*	*r*	*r*	*5.2*	*0.2*	*12*	*3.6*	*0.2*	*0*	*60*
Lithic-rich tuffs of Area 20 (8)	*42*	*0.1*	*0.3*	*0*	*r*	*r*	*33*	*21*	*1.2*	*1.8*	*+99*

[1] Low content of allanite and probable limit of detection of sphene in Topopah Spring not significant for this comparison.

[2] Biotite percentage disproportionately low with respect to other mafic minerals owing to oxidation to magnetite.

PAINTBRUSH TUFF AND ROCKS RELATED TO CLAIM CANYON CAULDRON

GENERAL FEATURES

ORIGINAL AND REDEFINITION OF THE PAINTBRUSH TUFF

The Paintbrush Tuff was defined by Orkild (1965, p. A49) from exposures in Paintbrush Canyon, a small gulch 6.4 km (4 mi) northeast of Yucca Mountain (figs. 1, 8). The most complete stratigraphic section, however, is on the north end of Yucca Mountain where four members are well exposed. The Topopah Spring and Tiva Canyon Members are widespread welded ash-flow sheets that were first defined as members of the former Oak Spring Formation (Hinrichs and Orkild, 1961, p. D97) in the Yucca Flat area (figs. 1, 2). These members were subsequently included in the Piapi Canyon Formation of the Oak Spring Group (Poole and McKeown, 1962, p. C61). The Yucca Mountain Member of the Piapi Canyon Formation was described by Lipman and Christiansen (1964) and occurs between the Topopah Spring and Tiva Canyon Members (fig. 7) in the Yucca Mountain area (fig. 8). Orkild (1965) included the Stockade Wash Member (Stockade Wash Tuff of this paper), the Topopah Spring Member, a newly defined Pah Canyon Member, and the Yucca Mountain and Tiva Canyon Members in his Paintbrush Tuff (fig. 7) of the Piapi Canyon Group.

The Paintbrush Tuff is here redefined to include, in ascending stratigraphic order, the Topopah Spring, Pah Canyon, Yucca Mountain, and Tiva Canyon Members and similar, quartz-poor, informal ash-flow and ash-fall tuffs that occur between the top of the underlying Stockade Wash Tuff, as herein defined, and the base of the overlying Rainier Mesa Member of the Timber Mountain Tuff, except for thin local bedded lithic-rich tuff that occurs just above the Stockade Wash (fig. 7). Excluded are the Stockade Wash Member, which was part of the original definition (Orkild, 1965), and also quartz-bearing, lithic-rich tuffs of the tuffs and rhyolites of Area 20, which occur between the Belted Range and Stockade Wash Tuffs and locally just above the Stockade Wash Tuff. In the Yucca Flat-Rainier Mesa area, these lithic-rich tuffs were included in the Paintbrush by Orkild (1965) as part of the now-abandoned Survey Butte Member (Poole and McKeown, 1962; Orkild, 1965) before the stratigraphic position of the lithic-rich tuffs in the subsurface of Area 20 was known (Orkild and others, 1968 and 1969). Where the Stockade Wash Tuff is missing, the lower contact of the Paintbrush can almost always be recognized within a few metres (several feet) as glassy quartz-poor friable tuff lying on zeolitic quartz-bearing lithic-rich tuff. In northeastern Yucca Flat and locally elsewhere in and around Yucca Flat (fig. 8), bedded tuff of the Paintbrush rests directly on the Belted Range Tuff or on a local thin peralkaline bedded sequence just above the Belted Range (Sargent and others, 1965; Noble and others, 1968).

BEDDED TUFF

The bedded tuff of the redefined Paintbrush, is generally recognized by the glassy state of contained shards and pumice lapilli and by its somewhat lesser induration than that of the underlying bedded tuff. The distinguishing

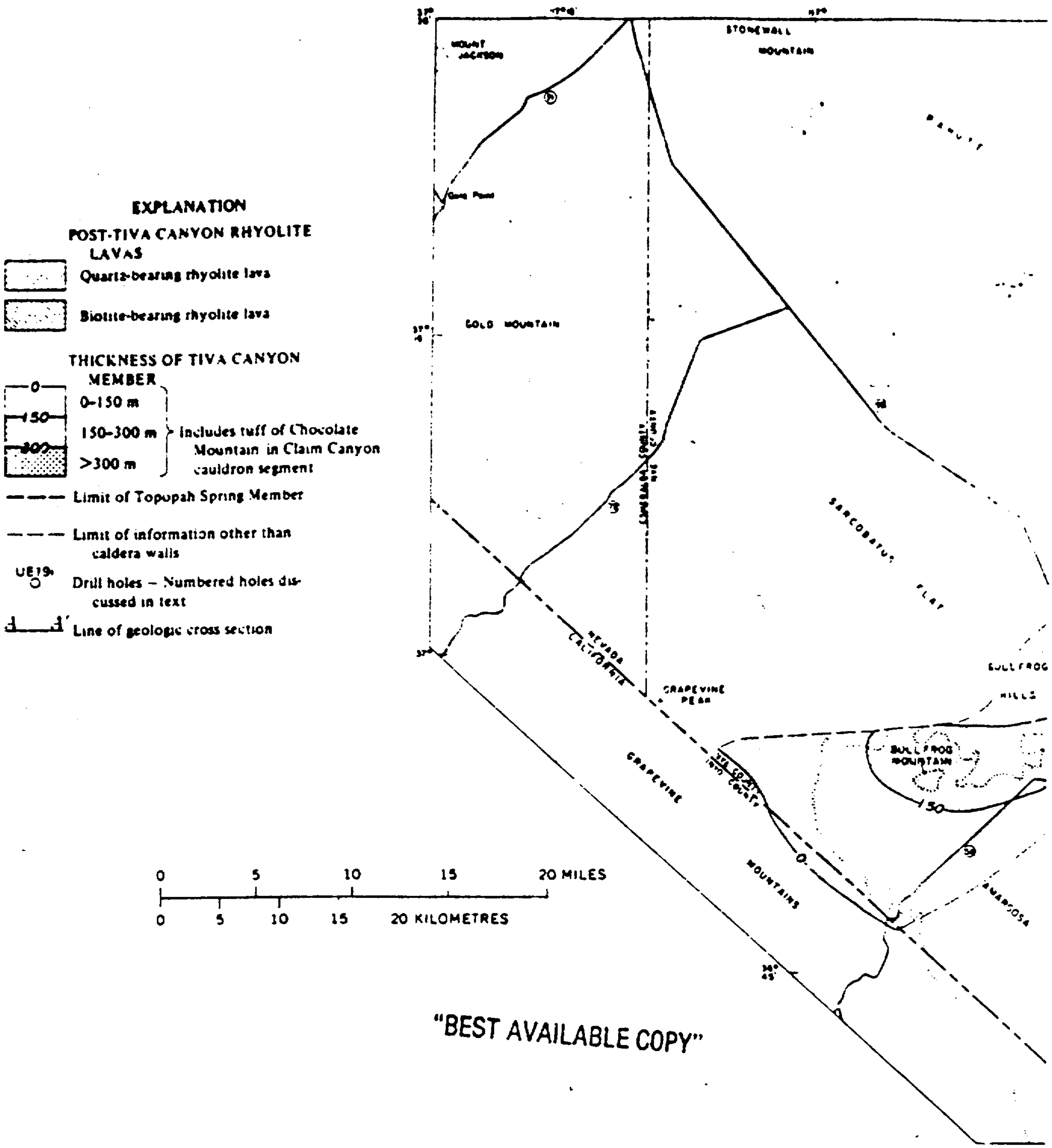


FIGURE 8.—Areal extent of Topopah Spring and Tiva Canyon Members of Paintbrush Tuff and related lavas. Isopachs of Tiva Canyon cross sections shown

petrographic feature of all except the uppermost part is the near absence of quartz, by comparison with the underlying and overlying rocks. In the uppermost 6–12 m (20–40 ft) of the bedded tuff, quartz increases upward and becomes dominant in the overlying Rainier Mesa Member of the Timber Mountain Tuff. The lower part of the bedded tuff, as observed in cores of some drill holes in Yucca Flat (fig. 8), has been locally zeolitized and indurated but, neverthe-

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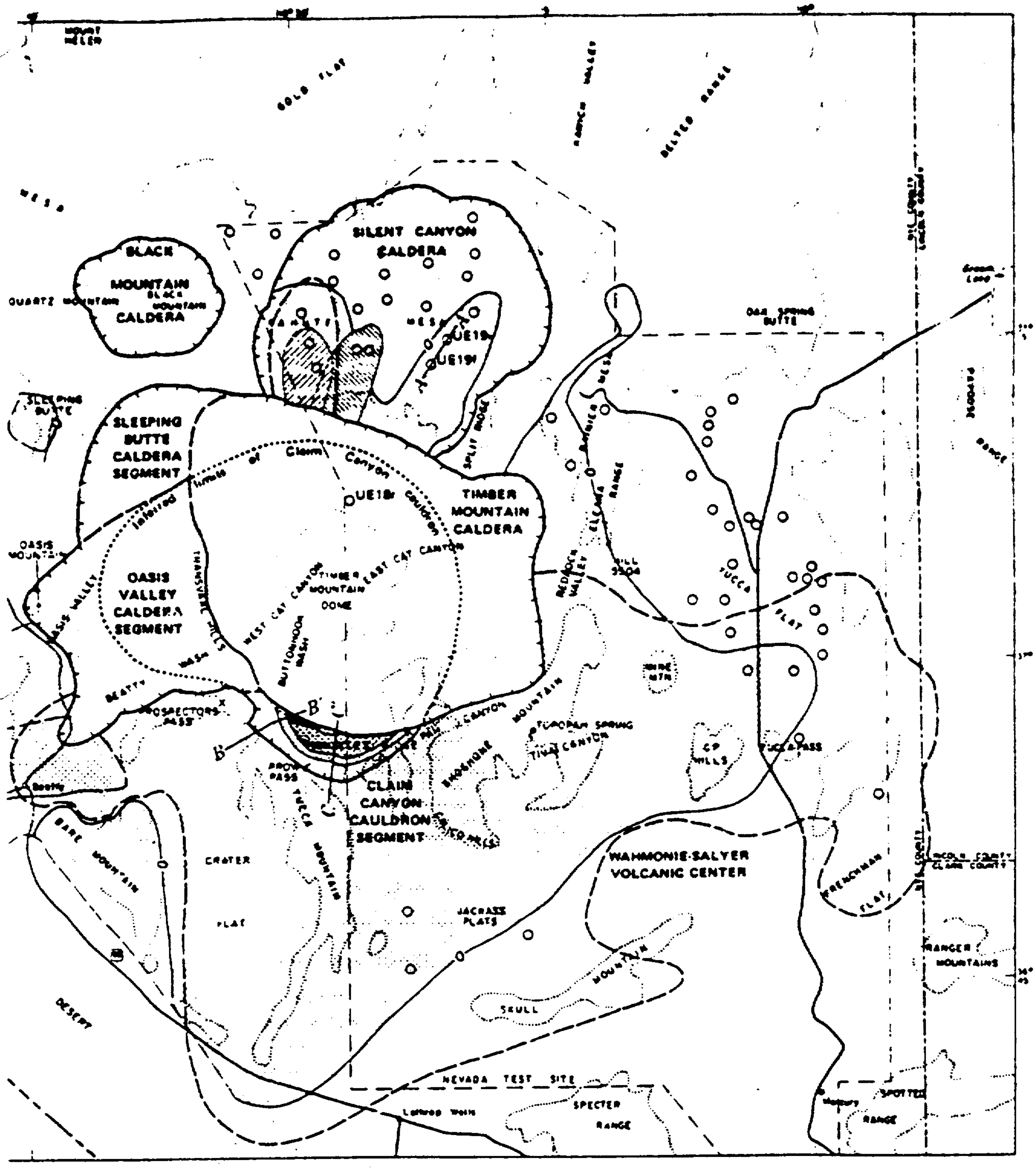


Member show great thickness of its uppermost subunit (tuff of Chocolate Mountain) within Claim Canyon cauldron segment. Geologic in figures 11, 12, and 13.

less, contains fewer lithic fragments and much less quartz than the underlying lithic-rich tuffs of the tuffs and rhyolites of Area 20. At a few places along the east wall of Timber Mountain caldera (fig. 8) where the lithic-rich tuffs are glassy, the base of the bedded tuff of the Paintbrush is at the top of the Stockade Wash Tuff. Although induration by zeolitization does, in places, cross the lower stratigraphic contact of the bedded tuff, the relative abundance of quartz and lithic fragments is the best criterion for separating the bedded tuff of the Paintbrush from the underlying lithic-rich tuffs of the tuffs and rhyolites of Area 20.

On the 7½-minute quadrangle maps (fig. 2), bedded tuff of the Paintbrush was not distinguished consistently from the underlying lithic-rich tuffs and from intertonguing bedded tuff of the Wahmonie Salyer volcanic center to the south (fig. 1; Poole, Carr, and Elston, 1965). Moreover, on the north and south rim of Timber Mountain caldera, some beds within the Paintbrush Tuff coarsen into tuff breccia toward lava vents and intertongue with rhyolite lava. In some places the tuff breccia was included with the lava flows; in others, it was mapped as bedded tuff. On the geologic map of the Timber Mountain caldera area (Byers and others, 1976), the bedded tuff map unit includes bedded tuff of the Paintbrush, lithic-rich bedded and nonwelded ash-flow tuffs of the tuffs and rhyolites of Area 20, tuff-breccia around rhyolite lava vents, and other minor local nonwelded ash flows, such as the tuff of Blacktop Buttes. The grouping together of all this light-colored porous tuff sequence that occurs between the underlying Belted Range Tuff and the overlying Timber Mountain Tuff was necessitated by the difficulty in separating these various units in the field within the time allotted for the completion of maps at the Nevada Test Site. Drill cores have provided the means for positive separation and identification of these units in the subsurface, in contrast to their generally low profile in outcrop.

GEOLOGIC RELATIONS BETWEEN WELDED ASH-FLOW TUFFS, LAVAS, AND CLAIM CANYON CAULDRON

Welded ash-flow tuff members of the Paintbrush Tuff intertongue with genetically related, alkali-calcic lavas that are not part of the Paintbrush and are within the Claim Canyon cauldron segment, which is the exposed high-standing southern remnant of the now largely buried Claim Canyon cauldron (fig. 8). Eruption of the members of the Paintbrush Tuff resulted in cauldron subsidence in overlapping areas within the inferred limits of the Claim Canyon cauldron shown in figure 8. All four tuff members are probably present within the buried part of Claim Canyon cauldron. The lowermost member, the Topopah Spring, is not exposed within the cauldron segment, but a fragment of intracauldron facies that was included in the Timber Mountain caldera debris flow was cored at a depth of 1,402 m (4,600 ft) in drill hole UE18r (fig. 8); hence, the site of UE18r was probably within the cauldron. North of Timber Mountain caldera, lavas intercalated with ash-flow tuff units are exposed in the wall of the caldera and were penetrated in drill holes north of the wall. Flow directions in the surface exposures indicate a southerly source (Cummings, 1964), probably from the rim area of the now-buried Claim Canyon cauldron within a few miles to the south.

Welded ash-flow tuffs of the Paintbrush Tuff and intercalated lavas are several times thicker (table 3) inside the Claim Canyon cauldron segment than where they are exposed on the cauldron rim (fig. 8). A total thickness of more than 3,000 m (6,500 ft) of Paintbrush Tuff and intercalated lavas is present inside the Claim Canyon cauldron segment, but the Topopah Spring Member is not exposed. The tuff of Chocolate Mountain and the tuff of Pinyon Pass are informal map units of the Paintbrush Tuff entirely within the Claim Canyon cauldron segment (see fig. 7). The tuff of Chocolate Mountain (table 3) is an extremely thick intracauldron welded quartz latite caprock of the Tiva Canyon Member and, at one critical exposure, grades downward within a stratigraphic interval of about 50 feet into the underlying main part of the Tiva Canyon Member. The tuff of Pinyon Pass is a separate overlying cooling unit which closely resembles the main part of the Tiva Canyon but is not considered part of it because of the complete cooling break between the units.

TABLE 3.—*Thicknesses and K-Ar ages of Paintbrush Tuff units and genetically related lavas within Claim Canyon cauldron segment and outside on cauldron rim*

[Modified from Byers and others (1980). K-Ar ages from Marvin and others (1970)]

Units, in stratigraphic order	Cauldron rim: Thickness (m)	Cauldron rim: K-Ar age (×10⁶ yr)	Cauldron segment: Thickness (m)	Cauldron segment: K-Ar age (×10⁶ yr)
Tuff of Pinyon Pass	0		150	
Tiva Canyon Member				
Tuff of Chocolate Mountain	0		600+	12.5, 12.6
Main sheet	120	12.4, 12.4	500+	12.6
Yucca Mountain Member	60		335	
Lavas between Pah Canyon and Yucca Mountain Members	30		300	
Pah Canyon Member	90		200+	
Pre-Pah Canyon lavas	0		150+	
Topopah Spring Member	120	13.2	Not exposed	
Composite thickness	420 (1,400 ft)		2,000+ (6,500+ ft)	

LITHOLOGY AND FIELD RECOGNITION

There are few unique criteria that can be used to distinguish individual welded tuff units of the Paintbrush Tuff in the field. Locally strong crystallization owing to slow cooling has destroyed primary textures, and so in places it is difficult to distinguish tuffs from intercalated lavas. The field geologist, following a long period of familiarization, eventually learns to distinguish on the basis of very subtle differences, individual cooling units in a restricted area. Part of the problem of field identification arises from the fact that lithologic variations within individual welded tuff units tend to be similar for all units and to be much more conspicuous than variations between equivalent parts of separate units.

All the welded ash-flow units of the Paintbrush Tuff and even the intercalated lavas have crystallization zones similar to those described by Smith (1960b), and most of the lithologic contrasts observed in outcrop are related to these zones. Color, for example, is related to crystallization zones in the following way: dark gray to black, glassy; brownish gray, cryptocrystalline; light brownish gray to purplish gray, microcrystalline; and light gray, coarsely microcrystalline with granophyric texture in pumice lenticles. The light-gray granophyric tuffs are typical of the thick intracauldron sheets. The degree of welding is also similar for each ash-flow cooling unit and tends to be moderate to dense except at the very distal edges of the units. Notwithstanding these similarities there are a few features, such as lithic content, pumice content and size, and compositional zonations, that the experienced geologist can use in making field identifications. Generally modal analyses are necessary to identify a unit.

TOPOPAH SPRING MEMBER

The Topopah Spring Member of the Paintbrush Tuff has been rather thoroughly described by Lipman, Christiansen, and O'Connor (1966); therefore, only the salient features are summarized here. The Topopah Spring, whose distribution is shown in figure 8, extends generally east of the Tiva Canyon Member but overlaps the member by more than 50 percent. Variations in thickness, with a maximum thickness of nearly 275 m (900 ft) on the west flank of the CP Hills (fig. 8), are mainly the result of paleotopography. The member is not exposed inside the Claim Canyon cauldron segment but an unknown volume of it is buried there. The total extracauldron volume is about 160 km^3 (40 mi^3) (Lipman, Christiansen, and O'Connor, 1966); probably more than 250 km^3 (60 mi^3) was erupted.

The unit has a high-silica rhyolitic lower zone and a quartz latitic upper zone or caprock. Near the south rim of the Claim Canyon cauldron segment (fig. 8) a middle xenolithic subunit containing granitic fragments separates the lower and upper parts (Lipman, Christiansen, and O'Connor, 1966, fig. 18). Densely welded quartz latitic bedded tuff, which occurs at Prospector Pass (fig. 8) just west of the cauldron segment, overlies the high-silica rhyolite zone and is probably very near the source area of the Topopah Spring area (Lipman, Christiansen, and O'Connor, 1966, p. F26).

The modal compositions of the lower and upper compositional zones are shown in figure 9; the Topopah Spring is distinguished modally from all other members of the Paintbrush Tuff by the lack of sphene. The rhyolitic lower part of the Topopah Spring is also distinguished readily by a high plagioclase-to-alkali feldspar ratio, but the quartz latitic caprock of the Topopah Spring is distinguished from younger caprocks of the Paintbrush mainly by the absence of sphene. Chemical analyses of the different ash-flow units of the Topopah Spring Member were published by Lipman, Christiansen, and O'Connor (1966, table 2); the silica ranges of the high-silica rhyolite and quartz latite are shown in figure 9.

The Topopah Spring Member can also be identified by its normal thermal remanent magnetization (G. D. Bath, written commun., 1965), in contrast to reverse polarities of younger units of the Paintbrush Tuff. Its K-Ar age is 13.2 m.y., in contrast to an average 12.5 m.y. for the Tiva Canyon Member (table 2).

PAH CANYON MEMBER AND RELATED PRE-PAH LAVAS

The Pah Canyon Member is lithologically similar to the quartz latitic caprock of the Topopah Spring Member but is a simple ash-flow cooling unit without compositional zoning. Also, its silica content—74 percent (fig. 9)—falls in the rhyolite range in contrast to that of the Topopah Spring caprock, which is in the quartz latite range of 69–72 percent. Flattened pumice lenticles, less than 2 cm in length, contrast with larger ones in the Topopah Spring. Sparse to common small cognate inclusions, mostly less than 0.5 cm, are distributed throughout the Pah Canyon. The extracauldron extent of the Pah Canyon is only about 200 km^2 (75 mi^2) (fig. 10). The extracauldron volume of the Pah Canyon does not exceed 20 km^3 (5 mi^3), but an equal or greater volume of the tuff must be contained within the Claim Canyon cauldron, for the average thickness of the tuff inside the cauldron is at least three times that of the tuff outside. The buried areal extent inside the cauldron is probably greater than that outside the cauldron.

Two lava flows underlie the Pah Canyon within the Claim Canyon cauldron segment (figs. 3, 7). Their modes are pooled and are similar to but slightly more mafic than that of the Pah Canyon (fig. 9). These pre-Pah Canyon lavas are the lowest stratigraphically in the Claim Canyon cauldron segment and are also closest to the cauldron wall, near which they are brecciated and silicified.

LAVAS AND ASH-FLOW TUFF BETWEEN PAH CANYON YUCCA MOUNTAIN MEMBERS

One or more lava flows of similar composition were extruded on the Pah Canyon Member before eruption of the Yucca Mountain Member within and just outside the Claim Canyon cauldron segment (fig. 10). At about the same time a local ash-flow tuff and two overlying lava flows were poured northward into Silent Canyon caldera (Cummings, 1964; David Cummings, written commun., 1964) from the now-buried Claim Canyon cauldron. The local ash-flow tuff to the north was penetrated only in drill holes UE19f and UE19i (fig. 10). On the north side of Timber Mountain caldera, the Pah Canyon and Yucca Mountain Members are not exposed or penetrated in drill holes, and so the local lavas and underlying tuff occur between the Topopah Spring and Tiva Canyon Members. The petrography (fig. 9) and cooling history of these local intercalated units on the north side, however, indicate that

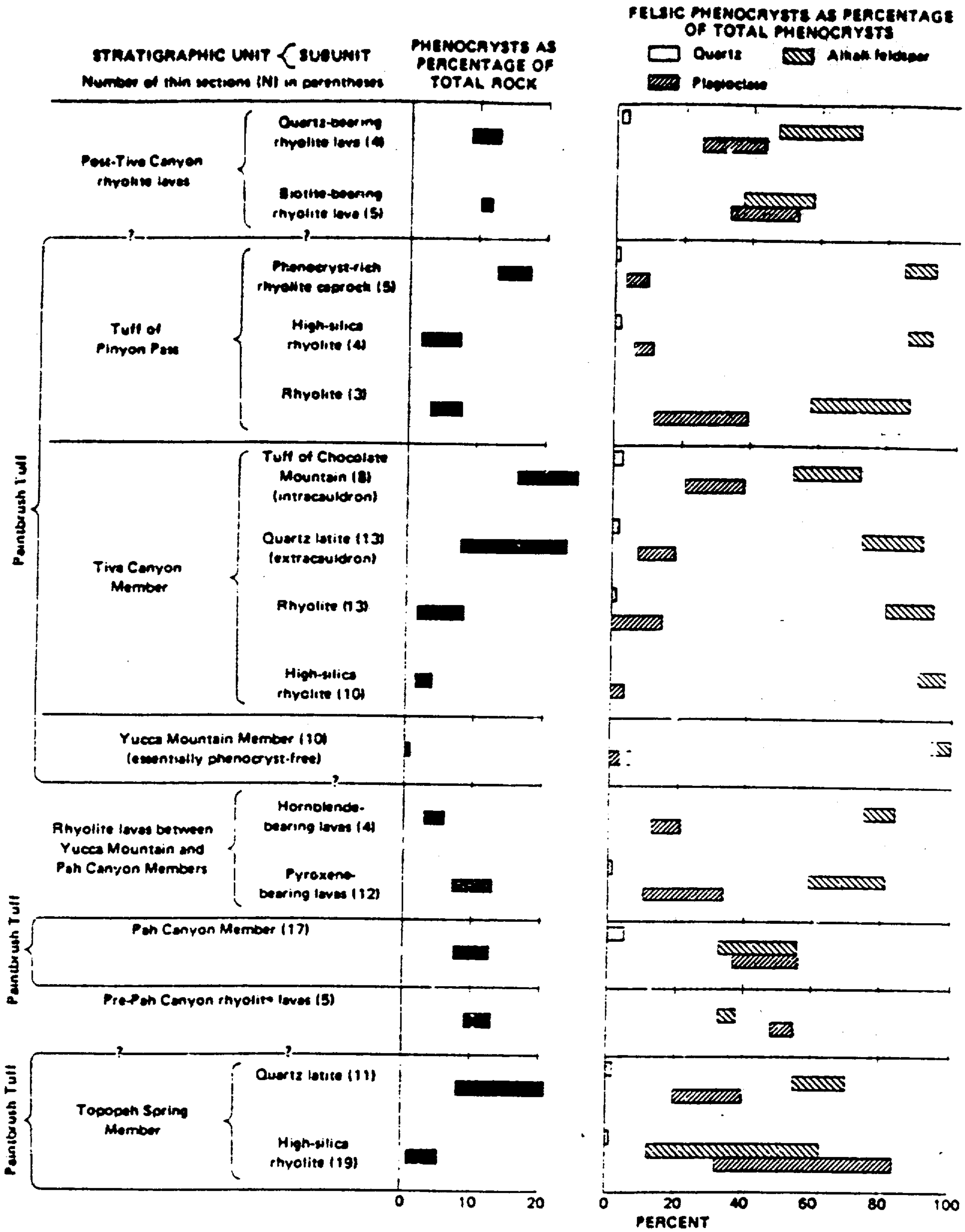
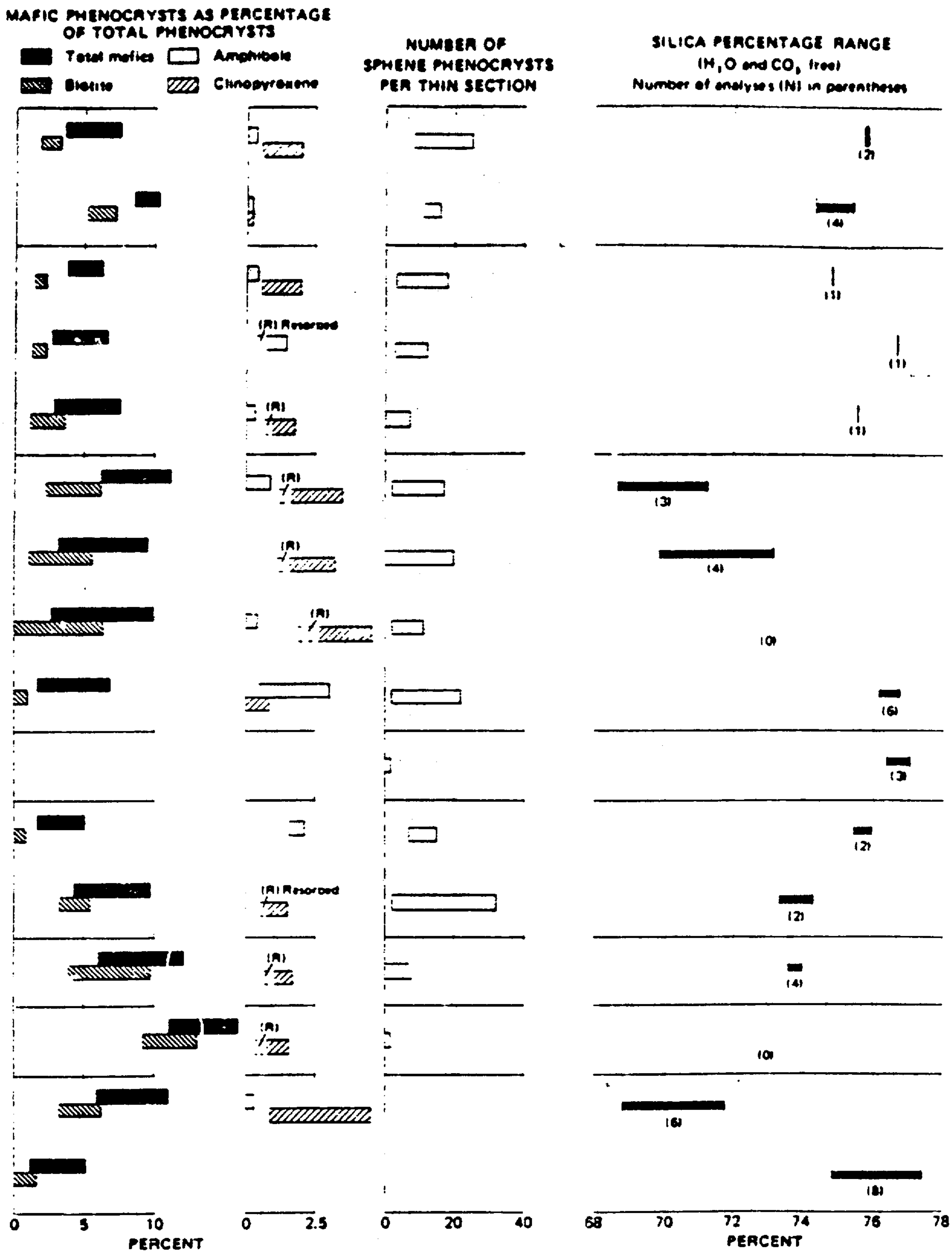


FIGURE 9.—Modal and silica ranges of significant units of Paintbrush Tuff and petrologically related lavas in order of stratigraphic sequences indicated by modal trends. Blank area in phenocryst column indicates absence of mineral. Modes of Topopah Spring and W. D. Quinlivan and P. W. Lipman (written commun., 1974).



...ccession. Queried successions between a few units inferred in part from structural relations and in part from general eruptive ...ember from Lipman, Christiansen, and O'Connor (1966). Silica percentages from Lipman, Christiansen, and O'Connor (1966)

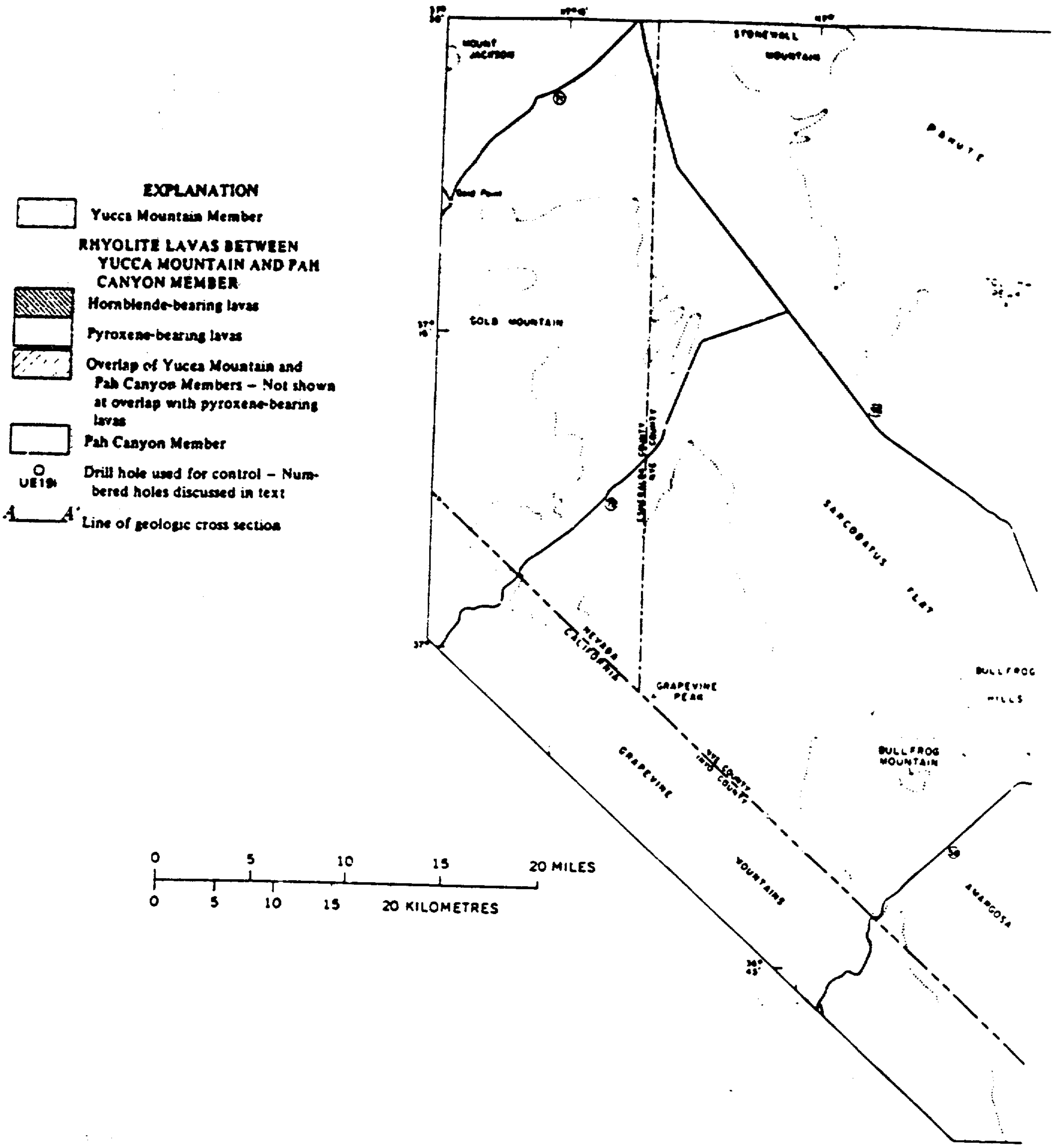


FIGURE 10.—Areal extent of Pah Canyon and Yucca Mountain Members of Paintbrush Tuff

they were probably extruded between the times of eruption of the Pah Canyon and Yucca Mountain Members. Where both members are exposed just outside the Claim Canyon cauldron segment, coarse-bedded ash-fall tuff, as much as 60 m (200 ft) thick, related to lava venting occurs between the members, except where two erosional remnants of lava fronts are preserved: one at the north end of Yucca Mountain and the other 3.2 km (2 mi) south of the head of Pah

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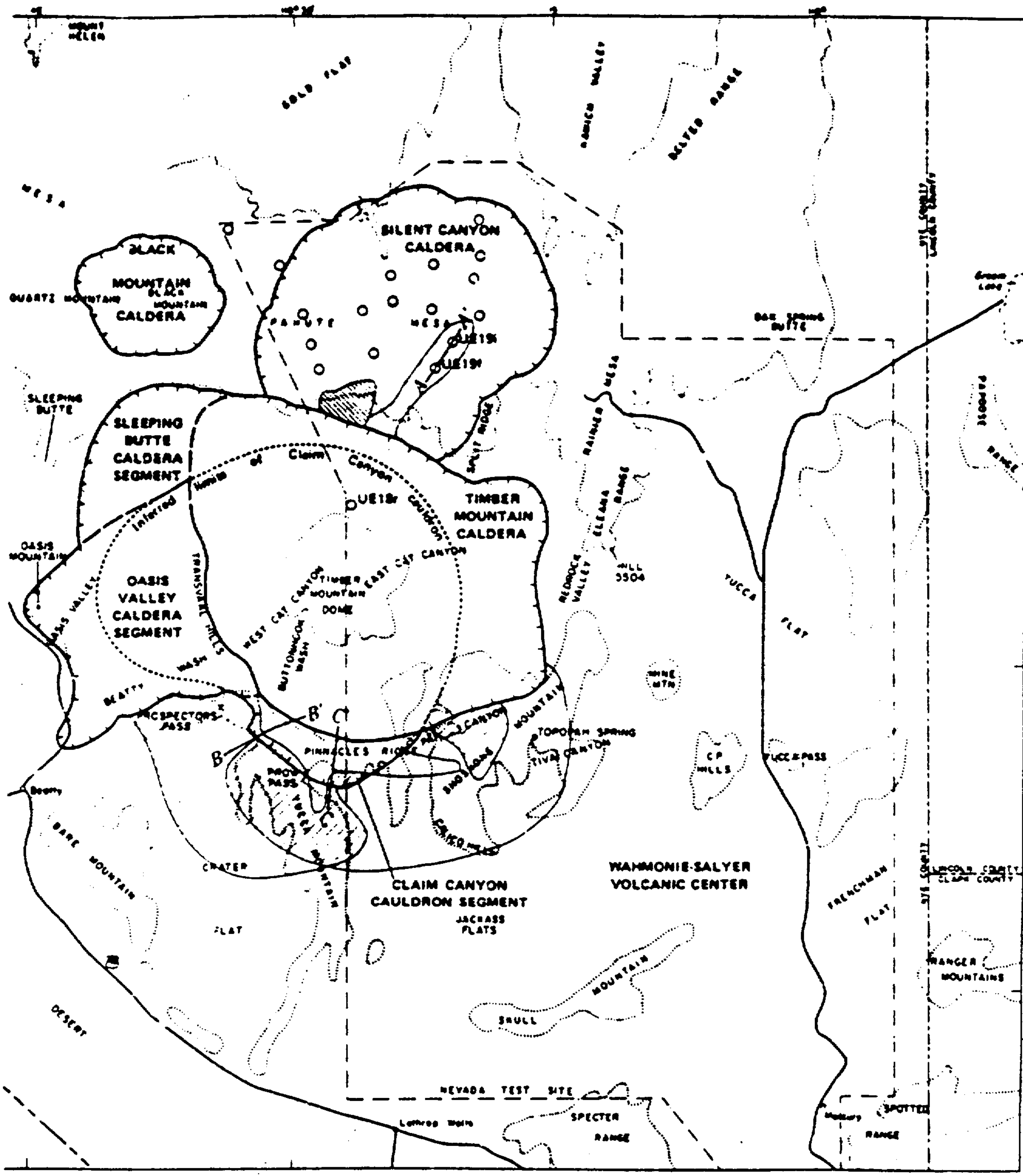


and extent of lavas between the members. Geologic cross sections shown in figures 11, 12, and 13.

Canyon (fig. 10). The local ash-flow tuff and all the lavas at this stratigraphic position on both north and south sides of Timber Mountain caldera have a thermal remanent magnetism that is reverse to the Earth's present field (G. D. Bath, written commun., 1965), and is typical of post-Topopah Spring units of the Paintbrush.

The lavas between the Pah Canyon and Yucca Mountain Members in Claim Canyon cauldron segment are pyroxene bearing and are almost identical in modal petrography to the lower lava flow on the north side in Silent Canyon caldera. These lavas differ from the Pah Canyon in that sphene is more common and alkali feldspar phenocrysts are dominant over plagioclase; the modal ranges shown in figure 9 represent seven thin-section modes from the south side pooled with five from the north side of the Timber Mountain-Oasis Valley caldera complex. The 74-percent silica content of the lower lavas indicates a rhyolitic composition similar to that of the Pah Canyon.

The local ash-flow tuff penetrated in drill holes UE19i and UE19f (fig. 10) is closely associated with the overlying pyroxene-bearing lava flow. This ash flow is locally fused beneath the lava flow, as penetrated in drill hole UE19f (figs. 10, 11). In drill hole UE19i, 4 km (2½ mi) farther away from the inferred volcanic source, the two units are separated by nonwelded tuff, and a basal vitrophyre is present in the lava. Although the tuff resembles the Pah Canyon Member lithologically and was shown as Pah Canyon in a cross section by Hinrichs, Krushensky, and Luft (1967, section *A-A'*), both the tuff and the overlying pyroxene-bearing rhyolite lava (Byers and Cummings, 1967) have similar phenocryst ratios (table 4). The subsurface tuff, moreover, differs modally from the Pah Canyon Member of the Paintbrush Tuff south of Timber Mountain caldera mainly in the sanidine/plagioclase phenocryst ratio (2:1). The Pah Canyon Member has about equal sanidine and plagioclase phenocrysts in the mode and contains other petrographic features that relate it more closely to the underlying Topopah Spring Member. The petrographic evidence and close association with the overlying pyroxene-bearing lava indicate that the local subsurface tuff is probably slightly later than the Pah Canyon Member and therefore is considered a local informal unit of the Paintbrush Tuff. The close spatial and temporal association of the tuff and the lava, combined with their close petrographic similarity also suggest that they were probably erupted from the same Claim Canyon cauldron vent, probably just inside the present north wall of the Timber Mountain caldera.

The upper, hornblende-bearing lava flows are exposed in the north wall of Timber Mountain caldera (fig. 10). They originally flowed only a short distance northward (Cummings, 1964; David Cummings, written commun.,

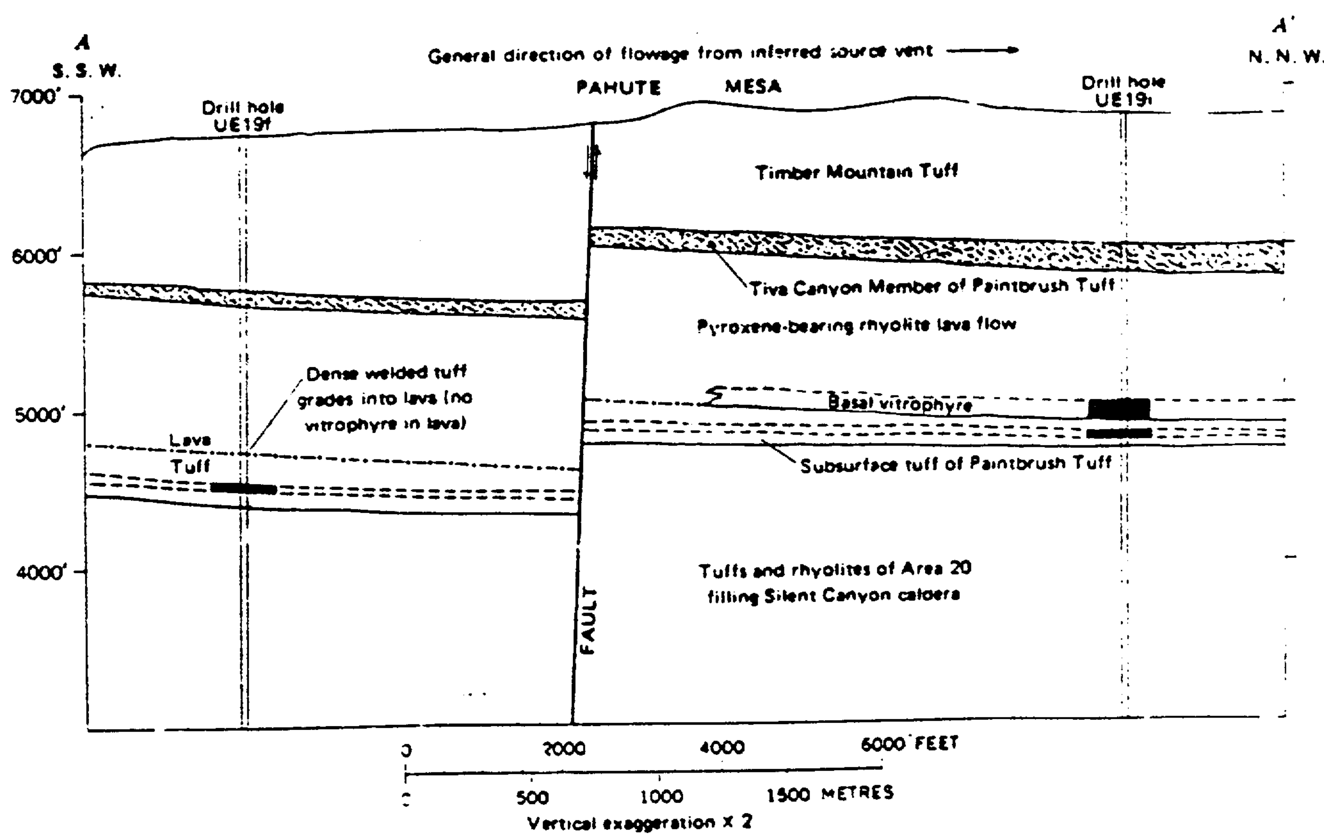


FIGURE 11.—Generalized section along *A-A'* through drill holes UE19f and UE19i, Silent Canyon caldera, showing relations between subsurface ash-flow tuff of Paintbrush Tuff and overlying, mineralogically similar pre-Tiva Canyon rhyolite lava. Vitrophyres shown in black; nonwelded to partially welded zones, stippled. Inferred transitional contact shown by dot-dash line. Line of section shown in figures 8, 10.

TABLE 4.—*Combined thin-section modes and computed accessory mineral percentages of local ash-flow tuff of Paintbrush Tuff and overlying pre-Tiva Canyon rhyolite lava where penetrated in drill hole UE19j, Pahute Mesa (fig. 11)*

[Location of drill hole shown in fig. 11. N.d., not determined]

Unit	Depth (m)	Phenocrysts as volume percent of total rock	Phenocrysts and accessory minerals as volume percent of total crystals: Quartz	Alkali feldspar	Plagioclase	Biotite	Clinopyroxene	Sphene	Allanite[1]	Zircon[1]	Apatite[1]	Total dark minerals[2]
Lava	429	10	0	62	29	5.0	([3])	0.9	N.d.	N.d.	N.d.	8.8
	524	9	0	64	29	3.5	([3])	1.0	0.4	0.2	0.03	7.1
	607	11	0	61	32	5.1	0.6	.3	.1	1	.03	7.1
Insignificant or partial cooling break?												
Tuff	655	14	1.9	64	29	2.5	.2	1.1	.3	.2	.03	5.7

[1]Accessory mineral percentages computed from counts of heavy mineral separates using sphene as control to combine thin-section mode and heavy-mineral count.

[2]Includes opaque oxides not tallied separately.

[3]Clinopyroxene altered in strongly devitrified interior of lava flow.

1964), as shown by the fact that they have not been penetrated by the extensive drilling in Silent Canyon caldera. Two lava flows of slightly different modal compositions are exposed. The volumetrically larger of the two lava flows is as much as 125 m (400 ft) thick and is separated from the underlying pyroxene-bearing rhyolite lava by 75 m (250 ft) of coarse, near-vent tuff breccia. The overlying Tiva Canyon Member pinches out over the thickest part of the larger hornblende-bearing lava flow. There are two exposures of this flow separated by a thick paleovalley filling or source-vent filling of post-Tiva Canyon biotite-bearing lava (Byers and Cummings, 1967; Byers and others, 1976). Two thin-section modes from each of the two exposures are very similar and are pooled on figure 9. Two chemical analyses (W. D. Quinlivan and P. W. Lipman, written commun., 1974) indicate that the hornblende-bearing lava approaches high-silica rhyolite in composition (fig. 9). One thin section from the smaller flow at the same stratigraphic position slightly west of the larger flow is petrographically similar but contains a subordinate amount of quartz phenocrysts.

YUCCA MOUNTAIN MEMBER

The Yucca Mountain Member (Lipman and Christiansen, 1964) is a simple cooling unit of uniform, nearly phenocryst-free, high-silica rhyolite (fig. 9) even where it is 335 m (1,100 ft) thick within the Claim Canyon cauldron segment (table 3). Outside the Claim Canyon cauldron segment, a small thin lobe is present east and south of Pah Canyon (fig. 10) and a larger lobe with a maximum thickness of about 75 m (250 ft) occupies about 100 km² (40 mi²) around northern Yucca Mountain and northern Crater Flat. Only about 8 km³ (2 mi³) is present outside the cauldron and roughly an equal volume can be inferred within the Claim Canyon cauldron segment.

The member differs from all other units of the Paintbrush Tuff, in having less than 1 percent phenocrysts, largely sodic sanidine. Sparse small pumice lenticles and grayish-red xenoliths less than 1 cm in length are strewn through a matrix of shards or devitrified groundmass. The unit has distinct crystallization zones with brownish-gray to gray glassy upper and lower zones and a pale-purplish-gray middle zone, which contains irregular white lithophysae where it is thick.

The field and petrochemical evidence indicate that the Yucca Mountain Member postdates not only the clinopyroxene-bearing lavas but probably also the hornblende-bearing lavas exposed in the north wall of Timber Mountain caldera where the Yucca Mountain is absent. Between the Yucca Mountain and overlying Tiva Canyon Member, only a foot or two of fine-grained ash-fall tuff, typical of the initial phase of the Tiva Canyon eruption, is nearly everywhere present; no coarse tuff breccia that would indicate nearby lava vents has been found between the members. This close stratigraphic association and the petrochemical trend toward increasing phenocrysts and decreasing silica content stratigraphically upward (fig. 9) indicate that the Yucca Mountain Member is an early eruptive phase of the same magma chamber that supplied the Tiva Canyon. Moreover, very little time, probably measurable in tens of years, elapsed between eruptions of the two members, for little if any erosion has been observed on the Yucca Mountain where it is overlain by the Tiva Canyon. The eruption of the Yucca Mountain, therefore, was probably very close to that of the Tiva Canyon Member in time and was almost certainly later than the extrusion of the hornblende-bearing rhyolite lava.

TIVA CANYON MEMBER

The Tiva Canyon Member consists of a main part—a compositionally zoned extensive ash-flow sheet—and an upper thick quartz latite, the tuff of Chocolate Mountain (Christiansen and Lipman, 1965; Byers and others, 1976), which is herein included as part of the redefined Tiva Canyon Member. Outside the Claim Canyon cauldron segment (fig. 8), the main part of the Tiva Canyon, like the Topopah Spring Member, is compositionally zoned (fig.

9); inside, the tuff of Chocolate Mountain overlies rhyolite of the lower main part of the Tiva Canyon above a thin transition zone characterized by crystal-rich quartz latitic pumice lenticles in a matrix of welded crystal-poor rhyolite.

In its type section at Tiva Canyon (fig. 8), the member is 107 m (350 ft) thick, and the maximum thickness, west of Beatty, is about 200 m (700 ft). The unit extends for about 115 km (10 mi) along a broad arcuate belt outside the southern wall of the Claim Canyon cauldron segment. The distribution of the member is similar to that of the Topopah Spring Member, except that the Tiva Canyon extends not as far east and somewhat farther west—just barely into California. The Tiva Canyon was mapped by Cornwall and Kleinhampl (1964) as cooling unit 3 of their Bullfrog Hills caldera. In Silent Canyon caldera, two lobes of the Tiva Canyon each about 105 m (350 ft) thick in separate areas were penetrated in five drill holes (fig. 8). Inside the Claim Canyon cauldron segment the lower main part of the Tiva Canyon and the upper part, the tuff of Chocolate Mountain, aggregate more than 900 m (3,000 ft) in thickness (table 2). The total area covered by the Tiva Canyon outside the cauldron is probably in excess of 2,600 km² (1,000 mi²) if the member extends northwest under Sarcobatus Flat (fig. 8). Inside the Claim Canyon cauldron, possibly as much as 520 km² (200 mi²) of tuff having a thickness averaging more than 0.8 km (0.5 mi), is now largely buried under younger rocks of the Timber Mountain-Oasis Valley caldera complex. The total volume of the Tiva Canyon Member, therefore, may be in excess of 1,000 km³ (250 mi³).

The Tiva Canyon Member is a compound cooling unit, predominantly gray to reddish-brown devitrified densely welded ash-flow tuff with minor light-brown and gray nonwelded to partially welded tuff at its base and top. Generally a few feet of genetically related light-gray ash-fall tuff occurs at the base of the unit. In the lowermost part the Tiva Canyon is crystal-poor sanidine- and hornblende-bearing high silica rhyolite tuff; it grades upward into a middle crystal-poor rhyolite with biotite, which is in turn overlain by an upper (caprock) crystal-rich quartz-latitic tuff (fig. 9). These three distinct compositional zones are laterally persistent over much of the sheet outside the Claim Canyon cauldron segment and, therefore, provide an intrasheet stratigraphy.

The Tiva Canyon Member inside the cauldron segment is locally flow-laminated and contains flow folds. Upward, it grades into normal welded tuff. This secondary flowage may have occurred where steep preemplacement topography marked the site of the cauldron wall. Welded caprock vitrophyre of the member is very thin in fault slices and blocks where it overlies tuff breccia near the cauldron wall, but locally the caprock vitrophyre grades downward into massive tuff breccia, possibly indicative of vent breccia related to the Tiva Canyon. The welded rhyolitic lower part thickens from a wedge-edge to nearly 300 m (1,000 ft) downdip, 3.2 km (2 mi) away from the cauldron wall (fig. 8). A 15-m (50-ft) stratigraphic transition zone between the lower flow-laminated, phenocryst-poor rhyolite of the main part of the Tiva Canyon and the overlying tuff of Chocolate Mountain is marked within the Claim Canyon cauldron segment by an increase of dark-gray phenocryst-rich collapsed pumice lenticles of quartz latite, similar to those in the overlying tuff of Chocolate Mountain. No xenoliths of the main rhyolitic part of the Tiva Canyon have yet been found in the tuff of Chocolate Mountain, although sparse xenoliths of the Yucca Mountain Member and older rocks are present. Because of these gradational relations and the lack of Tiva Canyon xenoliths, the tuff of Chocolate Mountain must be the upper part of one compound cooling unit that includes the widespread main sheet of the Tiva Canyon.

The tuff of Chocolate Mountain contains three compositionally similar subunits that were mapped by Christiansen and Lipman (1965); near the cauldron walls the subunits are separated by beds of yellow tuff breccia that thin and pinch out within a few kilometres northward (figs. 12, 13; Byers and others, 1976). The lower subunit is slightly more than 300 m (1,000 ft) thick and is largely gray devitrified tuff with granophyric pumice. The middle and upper subunits are brown and purple devitrified tuff locally underlain by basal vitrophyres indicative of partial cooling breaks. Petrographically, the tuff of Chocolate Mountain differs from the quartz latite caprock of the main part of the Tiva Canyon in containing abundant resorbed feldspar phenocrysts, a higher ratio of plagioclase to total feldspar phenocrysts (fig. 9), and sparse rather than very sparse hornblende phenocrysts. Although there is an overlap in content of silica (fig. 9) and other constituents (W. D. Quinlivan and P. W. Lipman, written commun., 1974) the petrographic differences indicate that the tuff of Chocolate Mountain is slightly more mafic than the main part of the Tiva Canyon outside the cauldron segment. At one locality within the cauldron segment, where a thick complete section is exposed in the south wall of Timber Mountain caldera (adjacent to the dikes between sections *B-B′* and *C-C′*, fig. 12), rhyolitic Tiva Canyon grades upward through about 15 m (50 ft) into typical extracauldron quartz latitic caprock of the Tiva Canyon. The transition upward to the typical tuff of Chocolate Mountain, however, is faulted out.

A tabular mass of fluidal flow-banded tuff of Chocolate Mountain 6 m (20 ft) thick dips moderately and is intercalated with coarse tuff-breccia. Near the head of Claim Canyon (fig. 12), this mass shows chilling above and below and may be a dike.

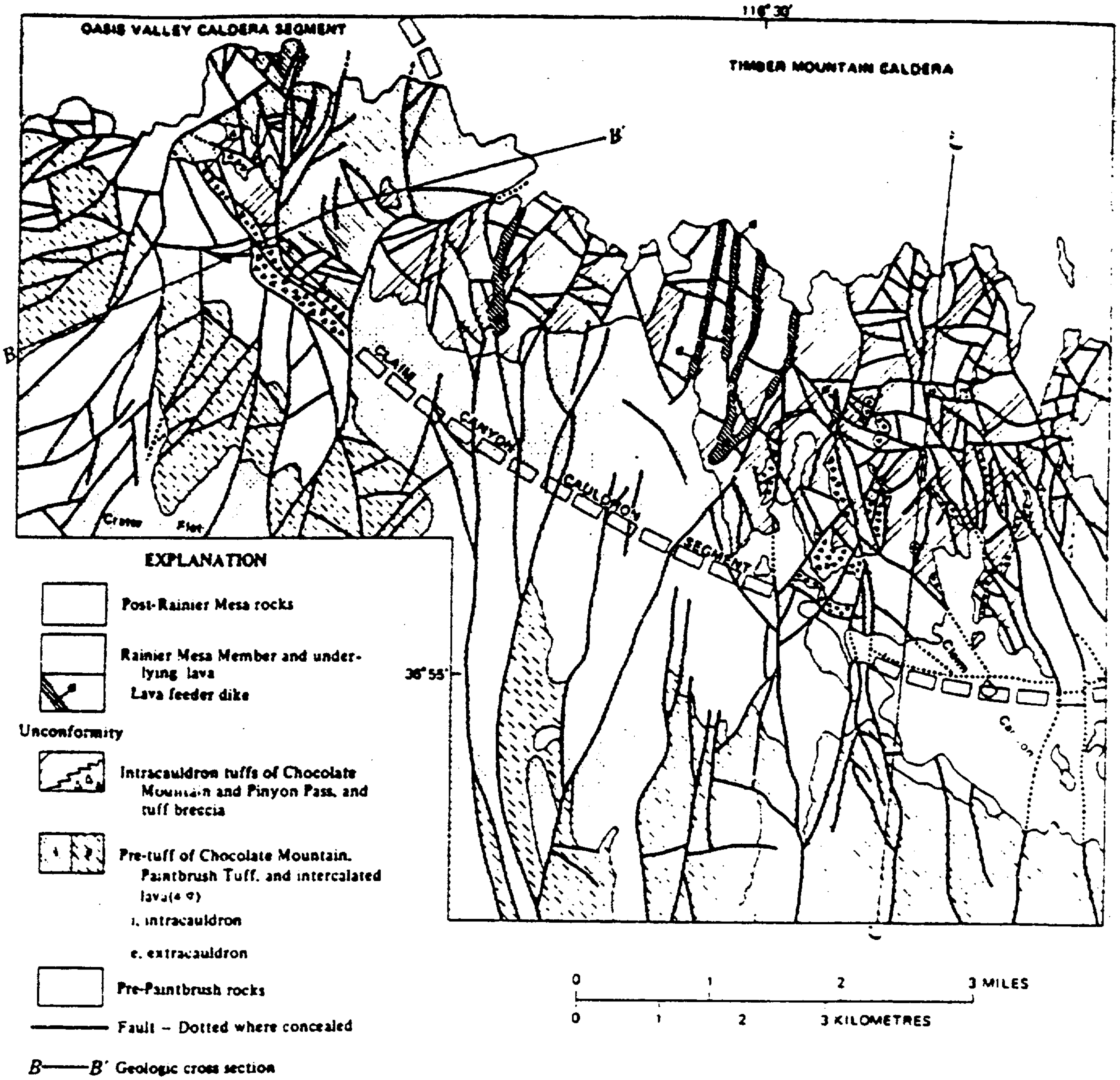


FIGURE 12.—Generalized geologic map of Claim Canyon cauldron segment and vicinity, showing greater intensity of faulting of tuffs within cauldron than outside. Generalized from geologic map of Timber Mountain caldera (Byers and others, 1976).

TUFF BRECCIAS WITHIN CLAIM CANYON CAULDRON SEGMENT

Tuff breccias intertongue with and overlie the tuff of Chocolate Mountain (Christiansen and Lipman, 1966; Byers and others, 1976) but are not included with the Paintbrush Tuff. These breccias are more than 150 m (500 ft) thick along the south wall of the Claim Canyon cauldron segment but wedge out within a mile or two north of the wall. Only the larger outcrops are shown in figure 12 (see Byers and others, 1976); the breccias shown in cross sections *B-B'* and *C-C'* in figure 13 are interpreted partly as vent breccias near the south wall of the cauldron. Within about 150 m (500 ft) of the cauldron wall, however, faulting and, locally, silicification have complicated interpretation of the origin of the breccia; there it is probably a landslide breccia consisting of rocks derived from the cauldron wall.

The breccia from an area about 150 m (500 ft) to 0.8 km (0.5 mi) from the cauldron wall contains, in order of decreasing abundance, large blocks of intracauldron Yucca Mountain and Pah Canyon Member, pyroxene-bearing sanidine-rich lava like that between the members, and sparse amounts of both members of Crater Flat Tuff. North of Crater Flat (fig. 12) this breccia locally includes a few giant blocks of welded rhyolitic Tiva Canyon about 30 m (100 ft) thick and 90 m (300 ft) long. These blocks dip steeply and are intricately crackled. The nonwelded matrix of the breccia is also modally rhyolitic Tiva Canyon and, moreover, grades upward in a few places to unaltered moderately to steeply dipping densely welded Tiva Canyon quartz latite or tuff of Chocolate Mountain. The nonwelded matrix is not crackled or highly fractured and the densely welded quartz latite locally occurs as steeply dipping vitrophyre lenses with contacts gradational into the matrix. This part of the tuff-breccia may be an explosion breccia genetically related to eruptive vents of the Tiva Canyon Member. Lipman's (1976) model of

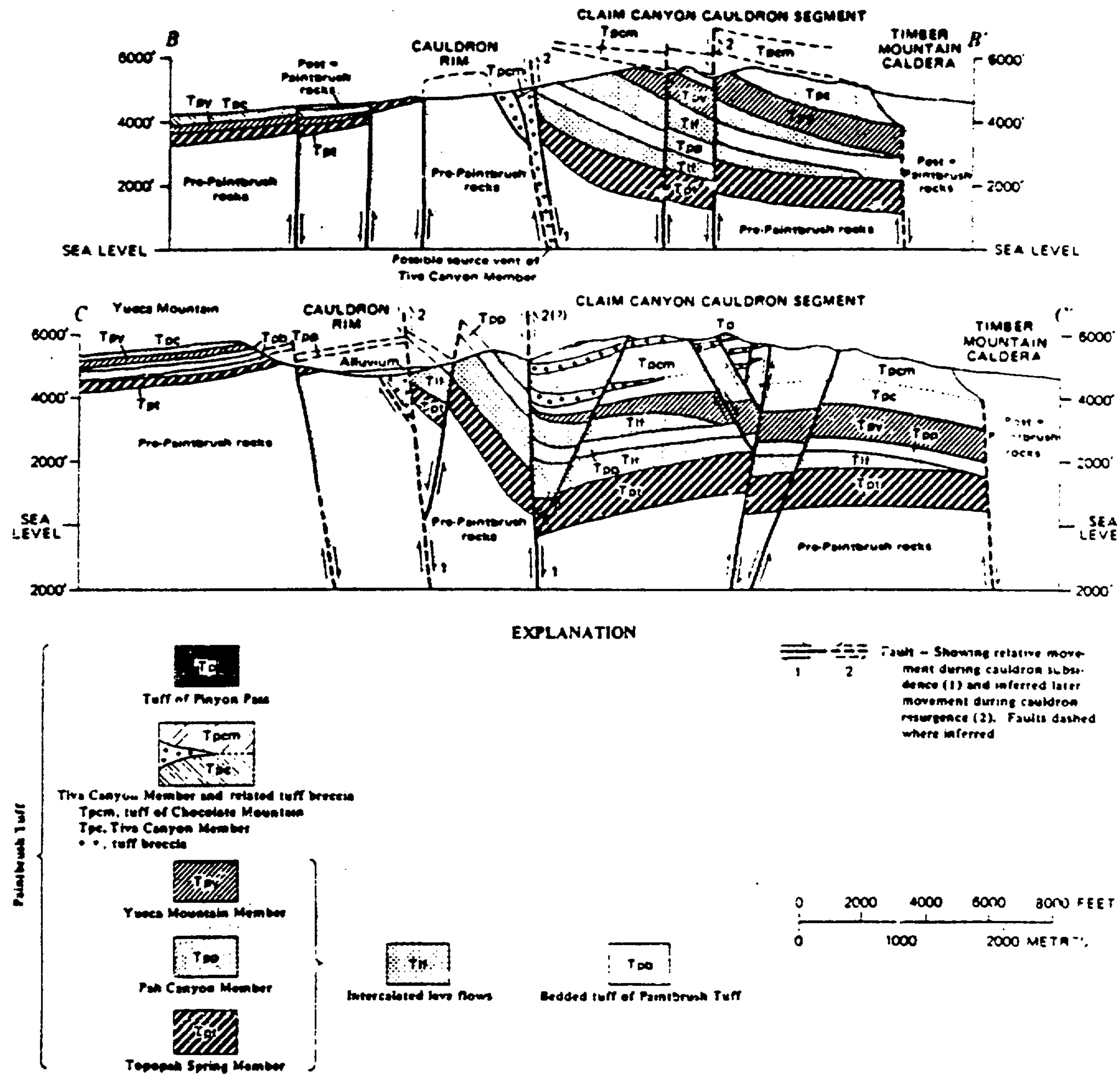


FIGURE 13.—Geologic sections through Claim Canyon cauldron segment, with critical units and faults projected above ground surface to indicate possible cauldron resurgence. Lines of sections shown in figure 12. Only major faults shown.

caldera collapse breccias in tuff associated with a caldera-forming eruption would also fit the above observations—except for the presence of intracauldron blocks.

Within the 150-m wide zone disturbed by faulting along the cauldron wall, a block of vertically dipping Topopah Spring Member was identified by thin-section examination. The contact of this breccia with the cauldron wall is locally exposed in Claim Canyon; it dips about 60° cauldronward and could be interpreted as the sole of a landslide.

In detail, the explosion tuff breccia differs from the breccias along the cauldron wall in that it is much less altered and is composed of about 50 percent blocks as much as 150 m (500 ft) long in a matrix of grayish-yellow tuff containing 0–20 percent angular clasts smaller than block size. More than 80 percent of the blocks are derived from Pah Canyon and Yucca Mountain Members. Moreover, the blocks contain a light-gray devitrified facies of these members that is typical of these units inside the cauldron. This yellow tuff breccia is similar in appearance to that in rhyolite vent tuff breccia cones; moreover, the grayish-yellow frothy matrix of rhyolitic Tiva Canyon mineralogy locally grades into a dark-gray pumiceous scoria. We would interpret these yellow tuff breccias that contain intracauldron clasts as originally at or near vent sites, probably those that erupted the Tiva Canyon Member.

Inward, about 2 km away from the cauldron wall (fig. 12), the tuff breccia thins and intertongues with the tuff of Chocolate Mountain and lies between the tuffs of Chocolate Mountain and Pinyon Pass. More than 3 km (2 mi) inward the tuff breccia tongues pinch out. These thin tongues of tuff breccia resemble the larger massive exposures to the south, except that the fragments are smaller and the tongues consist of a significant minor fraction of pre-Tiva Canyon rocks other than Pah Canyon and Yucca Mountain Members.

TUFF OF PINYON PASS

The tuff of Pinyon Pass is confined to the Claim Canyon cauldron segment and is here included as an informally named unit of the Paintbrush Tuff. The tuff is a multiple-flow simple cooling unit as much as 150 m (500 ft) thick, distinguished in the field by its generally moderate, rather than dense, welding, lack of vitrophyres, and stratigraphic position above the tuff of Chocolate Mountain. The tuff of Pinyon Pass is mapped with the tuff of Chocolate Mountain in figure 12, but is shown separately in section C–C′ (fig. 13), and on the geologic map (Byers and others, 1976). The lower nonwelded to partially welded rhyolitic zone, as much as 90 m (300 ft) thick, is commonly brilliant pink or light red where partially welded. Where the unit is thickest, however, the upper quartz latitic, most densely welded devitrified tuff is very much like the Chocolate Mountain in outcrop appearance; indeed, the flattened quartz latitic pumice lentils of the Pinyon Pass and Chocolate Mountain are identical in composition. The Pinyon Pass everywhere is concordant on the tuff of Chocolate Mountain or on tuff breccia that intertongues between the units. Very slight erosion of the upper part of the tuff of Chocolate Mountain before deposition of the tuff of Pinyon Pass is indicated locally by channeling and by absence of the nonwelded top of the tuff of Chocolate Mountain.

The tuff of Pinyon Pass is a compositionally zoned compound cooling unit and petrographically resembles the main part of the Tiva Canyon Member outside the Claim Canyon cauldron segment. The lower rhyolitic subunit, however, contains sparse dark, phenocryst-rich quartz latite lenticles, as much as 15 cm (6 in.) in length, typical of the underlying tuff of Chocolate Mountain. Hornblende is also very sparse or lacking (fig. 9) in the lower rhyolitic subunit of the tuff of Pinyon Pass, in contrast to the universal occurrence of hornblende and lack of biotite in the lower rhyolitic subunit of the Tiva Canyon Member. The middle unit is a high-silica rhyolite that contains a little hornblende and could be mistaken for either the lower or middle part of the Tiva Canyon. The upper crystal-rich compositional zone is more silicic than the analogous part of the Tiva Canyon (fig. 9) but considerable overlap in phenocryst percentages makes distinction by means of thin-section modes highly uncertain. The stratigraphic position of the tuff of Pinyon Pass above the tuff of Chocolate Mountain is the best criterion for identification. Chemical analyses of the unit (fig. 9; W. D. Quinlivan and P. W. Lipman, written commun., 1974) corroborate the observed compositional zonation from rhyolite, upward to high-silica rhyolite, to low-silica rhyolite in the crystal-rich caprock.

The close resemblance of the tuff of Pinyon Pass to that of the Tiva Canyon and the presence of Chocolate Mountain-type pumice lenticles in the lowermost part of the tuff of Pinyon Pass, despite slight local erosion of the underlying tuff of Chocolate Mountain, suggest that the tuff of Pinyon Pass was erupted within the Claim Canyon cauldron only a short time, perhaps within a few thousand years, after the Tiva Canyon Member was erupted. The lack of any bedded tuff breccia other than the single tongue that thins away from the cauldron wall suggests that no rhyolitic lava volcanism intervened between the tuff of Pinyon Pass and the underlying tuff of Chocolate Mountain. The tuff of Pinyon Pass, therefore, probably predates post-Tiva Canyon rhyolite lavas in the north wall of Timber Mountain caldera (fig. 8).

POST-TIVA CANYON RHYOLITE LAVAS

Two rhyolite lavas related to but not part of the Paintbrush Tuff are exposed in the north wall of Timber Mountain caldera (fig. 8) above the Tiva Canyon Member. These lavas are similar in physical appearance except that the lower flow has visibly more and larger biotite flakes. Petrographically, they are easily distinguished, for the upper rhyolite lava has sparse small quartz euhedra, whereas the more mafic lower rhyolite lava has none. These two flows were mapped separately in the Scrugham Peak quadrangle (Byers and Cummings, 1967).

Outcrop thicknesses of the individual flows average about 150 m (500 ft), but within a few miles downdip under Pahute Mesa the quartz-bearing flow attains 347 m (1,140 ft) in a drill hole. The flows extend a few miles north and northeast under Pahute Mesa, where they have been penetrated in drill holes (fig. 8). Drill records indicate that approximately 64 km² (25 mi²) of the mesa is underlain by either one or both of the rhyolites. The thickening of these lavas under Pahute Mesa, as inferred for the earlier lavas intercalated with the Paintbrush, is doubtless related to the existence of the Silent Canyon caldera, into which these later lavas also flowed.

The lower biotite-bearing lava exposures in the north wall of Timber Mountain caldera (fig. 8) are instructive relative to the source of the lava and the location of the Claim Canyon cauldron wall. The lava has fused underlying bedded tuffs and locally the basal vitrophyre zone cuts across the bedded tuff. Relict bedding visible below the flow within this vitrophyre indicates that the vitrophyre is a fused tuff. Tongues of vitrophyric agglutinated ash-fall tuff are also intercalated in the bedded tuff near the fused zone, suggesting a nearby source for these pyroclastics and the associated flow. Northerly flow azimuths (Cummings, 1964; David Cummings, written commun., 1964) indicate the source to the south, probably just inside the present wall of Timber Mountain caldera. Petrographically, the lavas clearly are late effusives related to the Paintbrush Tuff (fig. 9). It is reasonable to assume that these flows were fed by radial fissures near the cauldron ring fault similar to feeders of the pre-Rainier Mesa lavas in the south wall of Timber Mountain caldera (fig. 12), thus providing additional corroborative evidence that the north wall of the Claim Canyon cauldron is probably buried within a few kilometres south of the north wall of Timber Mountain caldera.

Petrographically and chemically, the two post-Tiva Canyon lavas are generally similar (fig. 9). Chemical analyses (W. D. Quinlivan and P. W. Lipman, written commun., 1974) reflect the minor petrographic differences between them. Probably of significance is the presence of euhedral quartz, ranging from 0.1 to 0.5 mm, amounting to several phenocrysts per thin section in the upper quartz-bearing flow. The small euhedral character of these quartz phenocrysts and their presence in all thin sections examined indicates that the magma from which the quartz-bearing flow was extruded had just attained the quartz-feldspar cotectic curve (Tuttle and Bowen, 1958), marking the change from the predominantly quartz-free volcanic rocks to overlying quartz-rich rocks of the Timber Mountain Tuff and related lavas.

CAULDRON SUBSIDENCES RELATED TO ERUPTION OF ASH-FLOW TUFF MEMBERS

The fact that nearly all units of the Paintbrush Tuff and intercalated, petrologically similar lavas thicken greatly (table 3) within the Claim Canyon cauldron segment suggests accumulation within a caldera. The notable exception is the Topopah Spring Member, the basal unit of the Paintbrush Tuff; from study of other calderas in the area, we presume that it is present at depth beneath the thick infilling units of the cauldron (fig. 12). The great thickness of the post-Topopah Spring units within the Claim Canyon cauldron segment plus the areal distribution of the Topopah Spring Member (fig. 8) and also the presence of the middle xenolithic zone and the bedded upper vitrophyre within a few kilometres of the rim of the Claim Canyon segment (compare with Lipman, Christiansen, and O'Connor, 1966, fig. 18) indicate that the segment is an eroded portion of a cauldron whose earliest subsidence was probably associated with the eruption of the Topopah Spring Member. The northern boundary of this cauldron is probably not too far south of the present north wall of Timber Mountain caldera, for lavas related to the Paintbrush were poured northerly into Silent Canyon caldera (fig. 10) from vents at or just south of this wall.

Additional suggestive evidence on the possible location of the north wall of Claim Canyon cauldron comes from a core taken at 1,402 m (4,600 ft) in drill hole UE18r. Debris flows associated with collapse of Timber Mountain caldera contain a few fragments of crystal-rich Topopah Spring caprock with granophyric pumice, typical of slowly cooled thick accumulations of ash-flow tuff within calderas. The occurrence of this granophyric Topopah Spring in the Timber Mountain caldera debris flows suggests that an intracauldron facies of the Topopah Spring Member was exposed within the present boundary of Timber Mountain caldera at the time of Timber Mountain caldera collapse. The northern limit of the collapse area associated with the eruption of the Topopah Spring Member, therefore, was probably north of drill hole UE18r, but south of the present north wall of Timber Mountain caldera (fig. 8).

Cataclysmic subsidence of the Claim Canyon cauldron segment during eruption of the Tiva Canyon Member is indicated by the thick accumulation of the main part and the tuff of Chocolate Mountain of the Tiva Canyon within the cauldron. Within the Claim Canyon cauldron segment, the tuff of Chocolate Mountain intertongues with tuff breccias related to the Tiva Canyon (section C–C′, fig. 13), possibly of vent breccia origin, for in many places they are modally like the Tiva Canyon and locally grade into welded Tiva Canyon quartz latite or tuff of Chocolate Mountain. These tuff breccias are coarse and thick just inside the cauldron wall but are thin and become finer away from the wall of the Claim Canyon cauldron segment. They were possibly largely derived from near-wall vents that were active during the emplacement of the Tiva Canyon. Moreover, these breccias contain pre-Tiva Canyon blocks of intracauldron facies as young as the Yucca Mountain Member, which immediately underlies the Tiva Canyon Member and may be considered an early eruptive phase of the Tiva Canyon. In a very few places within a kilometre of the cauldron wall, giant crackled blocks of dense welded Tiva Canyon occur in the massive tuff breccia and may have been autobrecciated in place during emplacement and subsequent collapse. Alternatively, these blocks may have been an early solidified phase of the Tiva Canyon that calved off the caldera rim during late stages of eruption and collapse, similar to the origin of the caldera breccias of the western San Juan Mountains, Colorado (Lipman, 1976). Under either hypothesis, however, the cauldron tuff breccias that are seen today just within the southern border of the Claim Canyon segment are a product of volcanism related to the Tiva Canyon and not to the Topopah Spring Member.

Indirect evidence also suggests that the Claim Canyon cauldron segment is a part of the collapse area related to eruption of the Tiva Canyon. The main part of the Tiva Canyon within the segment locally contains fluidal flow folds like a rhyolite lava, suggesting flowage while a caldera wall slope was being formed during emplacement and compaction related to welding. Only within the cauldron segment have flow folds been observed within the Tiva Canyon.

The walls of the two caldera collapses associated with the eruptions of the Topopah Spring and Tiva Canyon Members are probably not far apart but are not readily identified because later structural movements in the vicinity of the cauldron wall have obscured evidence of earlier collapses. Evidence of the wall related to Topopah Spring collapse is probably preserved in the vicinity of Claim Canyon just outside the fault that repeats the thickened Pah Canyon and the rhyolite lava under it (section C-C', fig. 12). Unfortunately, this part of the wall is covered by the alluvium flooring Claim Canyon. Unraveling the sequence of events along the cauldron wall probably can be accomplished only by detailed geologic mapping at a scale significantly larger than that (1:24,000) of the quadrangle maps (fig. 2).

Specific collapses related to the eruptions of the Pah Canyon and Yucca Mountain Members are also difficult to document. They and the intercalated lavas have a much greater thickness, fivefold to sixfold, inside the cauldron than outside; the total thickness of the units between the Topopah Spring and Tiva Canyon Members is 180 m (600 ft) on the cauldron rim (table 3) compared to about 1,000 m (3,300 ft) within the cauldron segment. We would interpret from sections B-B' and C-C' (fig. 13) that the top of the Topopah Spring within the main part of the cauldron segment would be at least 820 m (1,000 m minus 180 m) below its top outside just after collapse related to the Yucca Mountain Member.

The preceding line of argument becomes even more compelling when the difference in thicknesses of the Tiva Canyon, inside and outside the cauldron, namely about 800 m (2,600 ft), is added to the 820 m (2,700 ft) net difference in thickness between the Topopah Spring and Tiva Canyon Members (table 3). That is, assuming no resurgence of the cauldron, the top of Topopah Spring must have been more than 1,600 m (about 1 mi) below its altitude on the rim of the Claim Canyon cauldron after the eruption of the Tiva Canyon Member. It is difficult to conceive of this much cauldron subsidence relief on the Topopah Spring immediately after its eruption, because the unit has a relatively small volume (200 km³) outside the cauldron. The Claim Canyon cauldron more likely preserves a record of episodic subsidence (fig. 13) associated with eruption of each of the members of the Paintbrush Tuff. Analogous to the caldera relief of the Topopah Spring Member of the Paintbrush Tuff, the Grouse Canyon Member of the Belted Range Tuff within the Silent Canyon caldera is today about 2 km below its elevation outside the caldera (Orkild and others, 1968, 1969), owing to later subsidence related to eruptions of many post-Grouse Canyon units.

In a related paper, Christiansen and others (1976) consider the regional structure and the overall pattern of distribution and thicknesses of members of the Paintbrush Tuff and suggest the Oasis Valley caldera segment, in contrast to the Claim Canyon cauldron segment, as the main area of collapse related to eruption of the Yucca Mountain and Tiva Canyon Members. The differences between the conclusions expressed by these authors (four of whom are also authors of the present report) and those expressed here are minor and involve mainly emphasis on possible contrasting source areas between the two lower and the two upper ash-flow tuff members of the Paintbrush Tuff.

POSSIBLE MAGMATIC RESURGENCE OF CLAIM CANYON CAULDRON

The Claim Canyon cauldron segment, in contrast to nearly all other penecontemporaneous cauldron structures of the southwestern Nevada ash-flow field, today stands topographically high, like many central Nevada cauldron structures that have been elevated by both resurgence and basin-range faulting. The notable local exception is the Timber Mountain resurgent dome to be described later. The cauldron segment is not structurally high in the sense that older rocks are exposed within it; in fact, generally younger rocks of the Paintbrush Tuff are exposed within the cauldron segment, analogous to the resurgent doming of the Ammonia Tanks Member of the Timber Mountain Tuff within Timber Mountain caldera. The present authors will attempt to point out some geometric relations that in our opinion suggest that magmatic resurgence of the Claim Canyon cauldron occurred prior to emplacement of the Rainier Mesa Member and its petrologically related underlying lavas, an idea already outlined in an abstract (Byers and others, 1969). Christiansen and others (1976) present structural evidence that the present position of the Claim Canyon cauldron segment is not due to magmatic resurgence related to Claim Canyon cauldron.

The geologic map shown on figure 12, which is generalized from the geologic map of Timber Mountain caldera (Byers and others, 1976), is included in the present report merely to show the great intensity and trend of faults within the cauldron segment, especially in that part where the tuffs of Chocolate Mountain and Pinyon Pass (K-Ar age, 12.5 m.y.) of late Paintbrush age are exposed. The Rainier Mesa Member (K-Ar age, 11.3 m.y.) and the underlying petrologically similar lava are affected mainly by basin-range faults that are approximately radial to the intensely faulted wall of the Claim Canyon cauldron segment; that is, the basin-range faults strike more northeasterly where the wall faults trend northwesterly at the west end of the segment. As pointed out by Christiansen, Lipman, Orkild, and Byers (1965, p. B46), movement on these radial basin-range type faults also occurred during broad doming of the Timber Mountain volcanic center, as well as during regional basin-range extension. Many of these radial faults can indeed be traced into the cauldron segment, but most terminate against the circumferential cauldron faults.

Closely spaced circumferential faults and radial cross faults shown in figure 12 are localized within the cauldron segment and probably are representative of the much larger Claim Canyon cauldron, most of which is buried by the later collapses of Timber Mountain caldera and the Oasis Valley caldera segment. The strong intensity of this fault system confined within the cauldron segment is interpreted as a marginal fault pattern related to resurgent doming, and it bears close similarity to the fault pattern in the ring fracture zone at the periphery of Timber Mountain resurgent dome (Carr, 1964, fig. 2; Carr and Quinlivan, 1968, fig. 1; Byers and others, 1976). That this resurgence took place before the eruptions of pre-Rainier Mesa lavas and the Rainier Member is shown by the near absence of circumferential faults in these later units (fig. 12).

Further strongly suggestive evidence that the Claim Canyon cauldron resurged following eruption of the Paintbrush Tuff is the structurally high position of the Pah Canyon Member and its reasonable former extension upward, prior to erosion (fig. 13). Also the main part and the tuff of Chocolate Mountain of the Tiva Canyon are structurally higher within the cauldron than outside the cauldron or just inside the wall (section *B–B'*, fig. 13). Minor faults of very little displacement are not shown in the cross sections in order to emphasize the stratigraphy and structural position of the units. The present authors are also aware that these observed relations between the intracauldron and extracauldron rocks could also have come about, without magmatic resurgence, by extensional basin-range faulting related to regional right-lateral transcurrent movement along the Walker Lane (Locke and others, 1940)—the cauldron segment remaining structurally high, while the radial extracauldron blocks subsided. We do not favor this alternative hypothesis as the local control, because the intense circumferential fault pattern within the cauldron segment indicates more movement than in the blocks outside and, moreover, is typical of an outer arcuate fault pattern of a magmatically resurgent dome.

TIMBER MOUNTAIN TUFF AND ROCKS RELATED TO TIMBER MOUNTAIN CALDERA

ORIGINAL DEFINITION AND REDEFINITION OF TIMBER MOUNTAIN TUFF

The Timber Mountain Tuff (Orkild, 1965, p. A46–A47) was originally defined to include the composite sequence shown in the left column of figure 7. This sequence comprised the Rainier Mesa Member at the base successively overlain by the tuff of Cat Canyon, the tuff of Transvaal (tuff of Camp Transvaal of Lipman, Quinlivan, and others, 1966), and the Ammonia Tanks Member. Thin bedded tuff sequences at the base of the ash-flow members were included with the overlying member.

The Timber Mountain Tuff is here redefined to include all quartz-bearing ash-flow tuffs and thin ash-fall tuffs erupted about 11 m.y. ago (Marvin and others, 1970) from the Timber Mountain caldera center—the type area (Orkild, 1965). The tuff includes in ascending order, the Rainier Mesa and Ammonia Tanks Members of the original definition and, as here redefined, the tuff of Buttonhook Wash (Carr and Quinlivan, 1966) and the tuff of Crooked Canyon (Byers and others, 1976). The known areal distribution of the two newly added informal units is confined within the Timber Mountain–Oasis Valley caldera complex (fig. 7). Outside the complex, in all surface exposures, the Ammonia Tanks Member is the upper unit of the Timber Mountain Tuff, as in the original definition (Orkild, 1965). The Ammonia Tanks Member is redefined on the basis of field and petrographic studies to include the tuff of Cat Canyon and the tuff of Transvaal (fig. 7, first column, Orkild, 1965; Carr and Quinlivan, 1966; Lipman, Quinlivan, and others, 1966).

These units are equivalent to part or all of the Ammonia Tanks, as mapped in many of the 7½-minute quadrangles of the Nevada Test Site region (fig. 2). Thin sequences of bedded ash-fall tuffs that are intercalated with the ash-flow units are included in the Timber Mountain Tuff and were generally included with the overlying ash-flow unit on quadrangle maps of the Nevada Test Site (fig. 2). A bedded ash-fall sequence above the Ammonia Tanks Member was penetrated in a few drill holes in Yucca Flat (fig. 7, column 2). This bedded tuff, however, is less than 5 m (15 ft) thick and has not been recognized in surface exposures.

Quartz phenocrysts as much as 3 mm long are common to abundant in both the ash-flow and associated thin ash-fall tuffs, in contrast to the absence or near-absence of quartz in the underlying and overlying stratigraphic units. An exception to this general statement is the uppermost several meters of the underlying bedded tuff, in which quartz crystals increase in abundance and size upward to the Paintbrush-Timber Mountain contact.

Several lithologic units, closely associated with the Timber Mountain Tuff in genesis or in time, were not included in the original definition (Orkild, 1965) and are here likewise excluded—analogous to the exclusion of similar units from the Paintbrush Tuff. These units include debris flows that intertongue with the Rainier Mesa Member, alkali-calcic rhyolite lavas, and tuff dikes and other intrusives on Timber Mountain resurgent dome. The ash-flow tuff members and informal tuff units of the Timber Mountain Tuff and their relations to coeval debris flows, lavas, and intrusive rocks, are discussed on following pages.

RAINIER MESA MEMBER

The Rainier Mesa Member, the basal member of the Timber Mountain Tuff, was originally described by Hinrichs and Orkild (1961, p. D97) from excellent exposures at Rainier Mesa (fig. 14). These authors included the Rainier Mesa Member as the uppermost member of the Oak Spring Formation. Poole and McKeown (1962, p. C61), a year later, included the Rainier Mesa Member as the uppermost unit of their Piapi Canyon Formation of the Oak Spring Group. Still later, Orkild (1965, p. A49) defined Timber Mountain Tuff (fig. 7) and placed the Rainier Mesa Member at the base.

An isopach map of the Rainier Mesa Member generalized from Byers and others (1968) is shown in figure 14. The Rainier Mesa is more than 500 m (1,500 ft) thick, and the base is not exposed in the west wall of Timber Mountain caldera, where the unit is densely welded and is strongly devitrified with granophyric texture in the pumice. The coarse textural features suggest that at least another hundred metres may be present in the unexposed lower part in the west wall. A thickness of 396 m (1,300 ft) was penetrated in a drill hole on Pahute Mesa. The total volume of the Rainier Mesa Member, as calculated from the isopach map, is in excess of 1,200 km³ (300 mi³).

The upper quartz latitic caprock of the Rainier Mesa Member was locally mapped along the wall of Timber Mountain caldera as the tuff of Falcon Canyon (Hinrichs and others, 1967; Orkild and others, 1969). This usage is not retained. This upper quartz latitic subunit is exposed within the caldera near the northeastern wall at test well 8 (fig. 14) and also in the bottom of Beatty Wash where it cuts the southwestern wall of the caldera. In both localities the quartz latite intertongues with debris flows (figs. 3 and 7). The debris flows pinch out northward in the southwest caldera wall and are absent where 450+ m (1,500+ ft) of Rainier Mesa Member is exposed in the Transvaal Hills (fig. 14). Here the quartz latitic subunit of the Rainier Mesa is slightly thicker than elsewhere outside the caldera, but only about 15 m (50 ft) of quartz latitic caprock was penetrated by drill hole UE18r. The upper quartz latitic subunit was emplaced during late stages of caldera collapse (Byers and others, 1969, p. 94–95), as exhibited by the intertonguing relations with the debris flows.

The Rainier Mesa Member is a compositionally zoned compound cooling unit consisting of an extensive high-silica rhyolite tuff overlain with a partial cooling break by a considerably thinner quartz latitic tuff that is restricted to the vicinity of Timber Mountain caldera. The rhyolitic subunit, where exposed outside the caldera, is commonly pink nonwelded shard tuff at the base grading upward into densely welded black vitrophyre (Byers and others, 1968, p. 93). The vitrophyre grades upward into dense brown to pale-red devitrified tuff with common white flattened pumice lenticles, ranging from 2.5 to 10 cm (1–4 in.). In the west wall of Timber Mountain caldera (fig. 14), the devitrified zone is coarser than elsewhere and the pumice is granophyric. In general, the devitrified zone grades upward into a light-gray crystalline zone with spherulitic sanidine and cristobalite in the pumice, typical of Smith's (1960b) vapor-phase zone. The vapor-phase zone of the high-silica rhyolite subunit commonly grades within a few feet into a vitrophyric or dark-brown cryptocrystalline quartz latite, which in turn grades upward into a second light-colored vapor phase zone, visible in only a few places because of erosion or colluvial cover. Dark quartz latitic pumice lenticles in the quartz latite are somewhat larger than the white rhyolitic pumice in the underlying rhyolite. Where the Rainier Mesa Member is 396 m (1,300 ft) thick in the drill hole in the west part of Silent Canyon caldera, the main cooling unit described above is underlain by a nonwelded phenocryst-poor pink shard tuff about 150 m (500 ft) thick. The phenocryst ratios are similar to those of the lower rhyolitic part of the overlying main cooling unit of the Rainier Mesa. These two tuffs may be separate cooling units, and the Rainier Mesa, like the overlying Ammonia Tanks Member, may be a composite sheet (Smith, 1960a, p. 812).

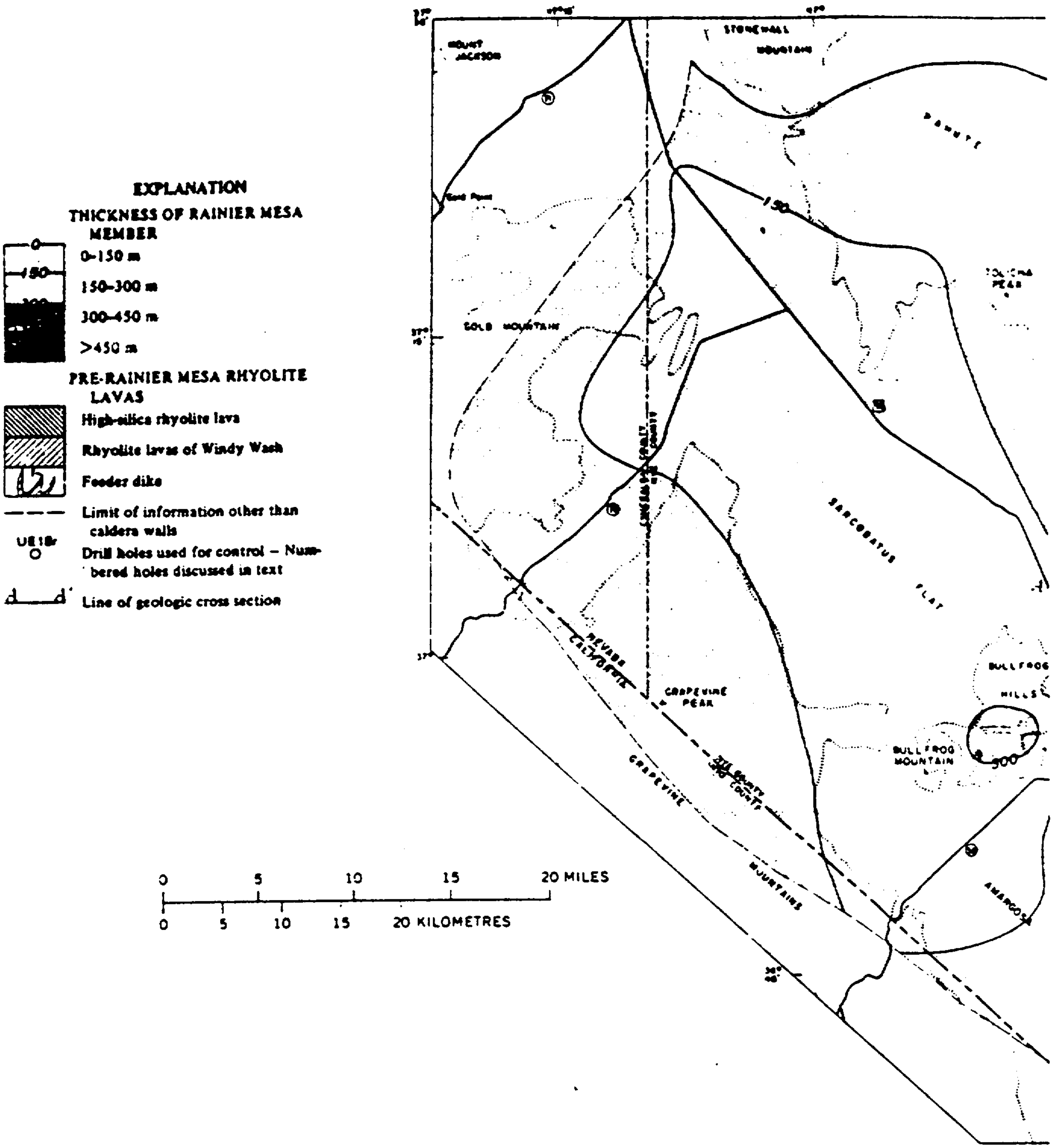
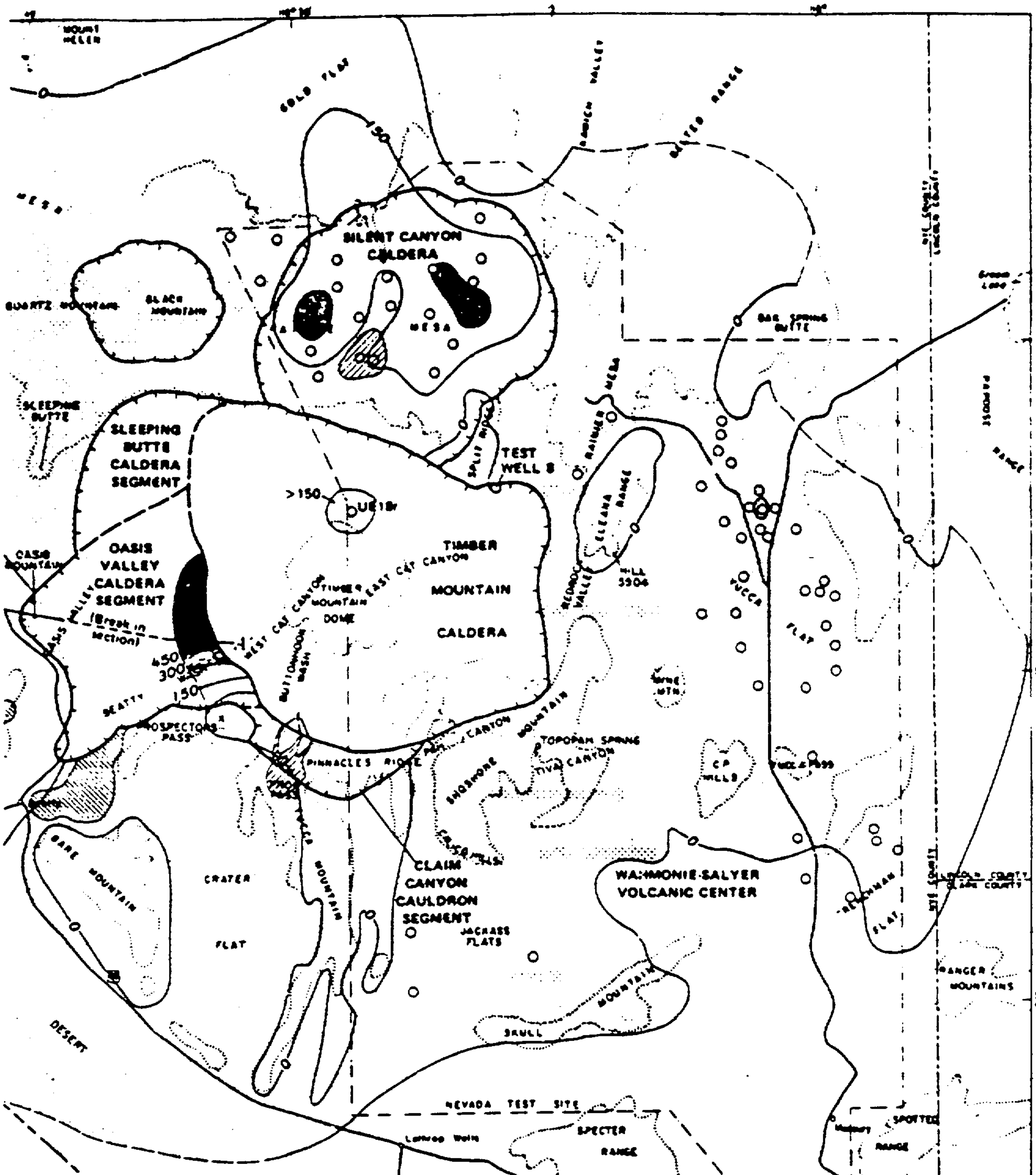


FIGURE 14.—Generalized isopach map of the Rainier Mesa Member of Timber Mountain Tuff and

The unique petrography of the Rainier Mesa Member distinguishes it from cooling units of the underlying Paintbrush Tuff, as well as from overlying units of the Timber Mountain Tuff (fig. 15). Analyses of 10 high-silica rhyolite samples show an average of about 77 percent silica, a percentage similar to that of the subunits of the



distribution of petrologically related, pre-Rainier Mesa lavas. Geologic cross section shown in figure 23.

Paintbrush Tuff (W. D. Quinlivan and P. W. Lipman, written commun., 1974, table 6; Lipman, 1966). The Rainier Mesa rhyolite, however, is crystal rich and contains quartz, in contrast to crystal-poor quartz-free rhyolites of the Paintbrush Tuff. The quartz latitic caprock contains a mixture of hornblende-rich and

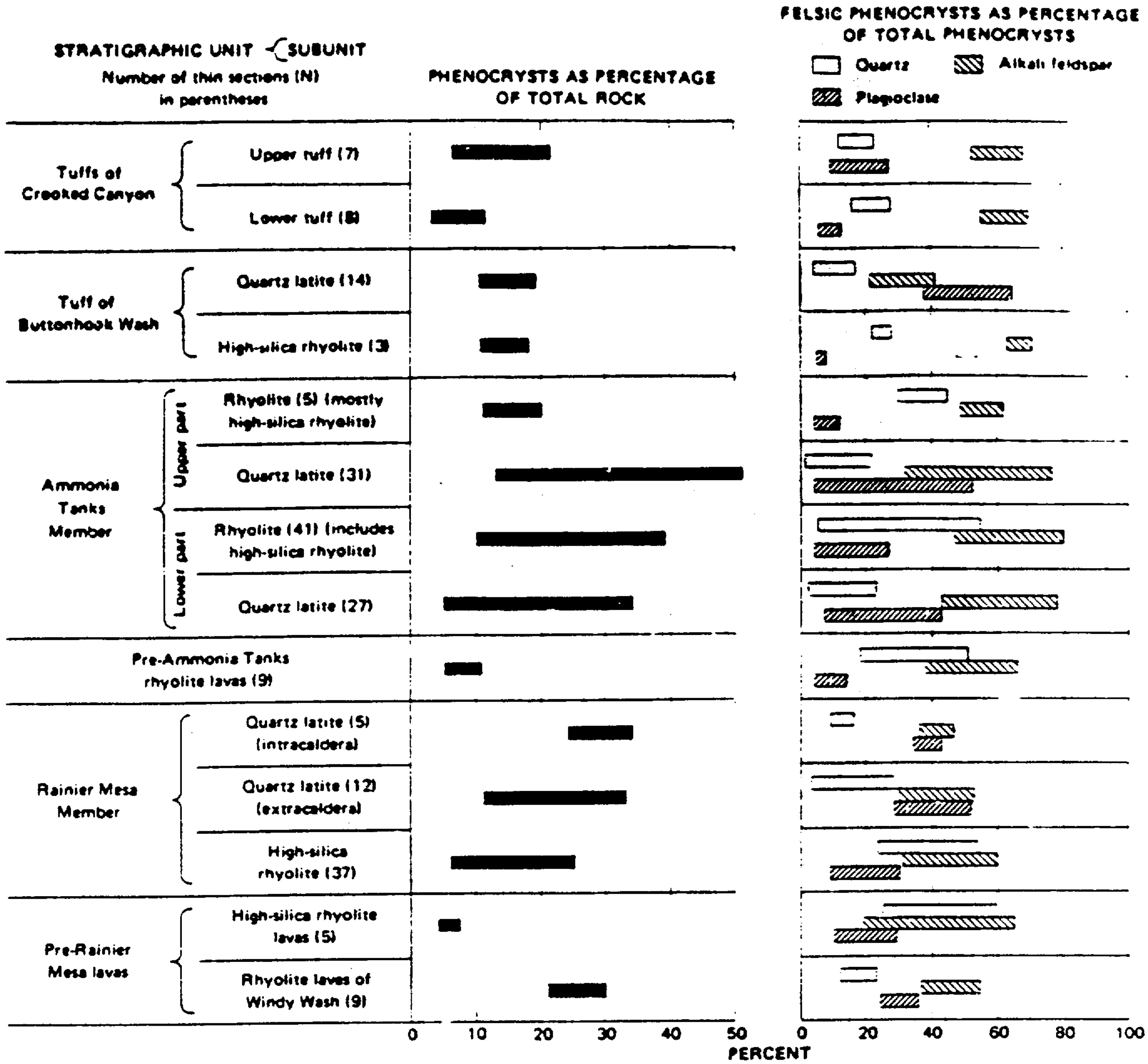
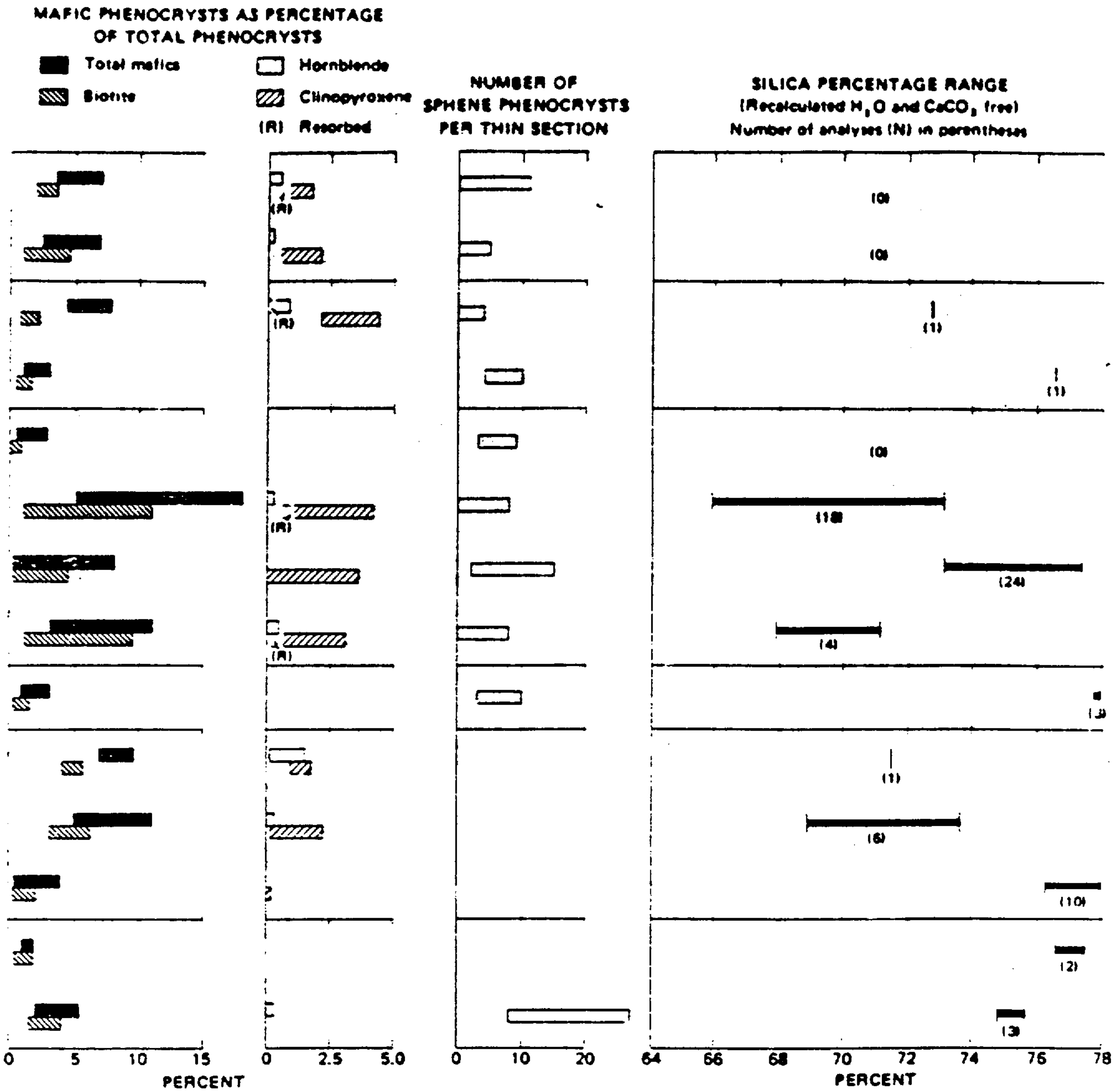


FIGURE 15.—Modal and silica ranges of units of Timber Mountain Tuff and petrologically related lavas in order of stratigraphic succession. (1962), Lipman (1966), and W. D. Quinlivan

clinopyroxene-rich mafic scoria pumices with subordinate quartz-rich rhyolitic pumice similar to that in the underlying rhyolite subunit (Byers and others, 1968, p. 95). The Rainier Mesa Member, like the Topopah Spring Member, differs from the overlying ash-flow units of the Timber Mountain Tuff in containing no sphene. The ratio of plagioclase to total feldspar phenocrysts is also higher in the Rainier Mesa high-silica rhyolite than in the rhyolites of overlying ash-flow units of the Timber Mountain Tuff. This feldspar phenocryst variation is similar to that in rhyolitic subunits of members of Paintbrush Tuff (fig. 9). Sanidine phenocrysts in the high-silica rhyolitic subunit of the Rainier Mesa are relatively potassic and have cryptoperthite rims in contrast to microperthitic sodic sanidine and anorthoclase in the rhyolites of younger cooling units of the Timber Mountain Tuff (O'Connor, 1963).

The Rainier Mesa Member of the Timber Mountain Tuff is the same unit as cooling unit 4 of Cornwall and Kleinhampl (1964, p. J10) in the Bullfrog Hills (fig. 14).



Modal analyses by F. M. Byers, W. D. Quinlivan, and J. T. O'Connor, and from Cornwall (1962, table 2). Silica percentages from Cornwall and P. W. Lipman (written commun., 1974)

The K-Ar age is 11.1 m.y. (Marvin and others, 1970), and the thermal remanent magnetization is reverse (G. D. Bath, written commun., 1965).

AMMONIA TANKS MEMBER

The Ammonia Tanks Member was defined by Orkild (1965) as the uppermost unit of the Timber Mountain Tuff; its type locality is at Ammonia Tanks (fig. 16). Because of evidence to be presented in the following paragraphs, the Ammonia Tanks is here redefined to include the tuff of Cat Canyon on Timber Mountain resurgent dome (Carr and Quinlivan, 1966) and the tuff of Transvaal (Orkild, 1965; tuff of Camp Transvaal of Lipman, Quinlivan, and others, 1966). (See fig. 7). An intracaldera section of the Ammonia Tanks is displayed at West Cat Canyon (fig. 16), where the tuff of Cat Canyon consists of a lower part of two mapped subunits, unit A and unit C (Lipman, Quinlivan, and others, 1966, section B-B'), which are more than 600 m (2,000 ft) thick and which are overlain by an upper part (unit E and unit F) about 300 m

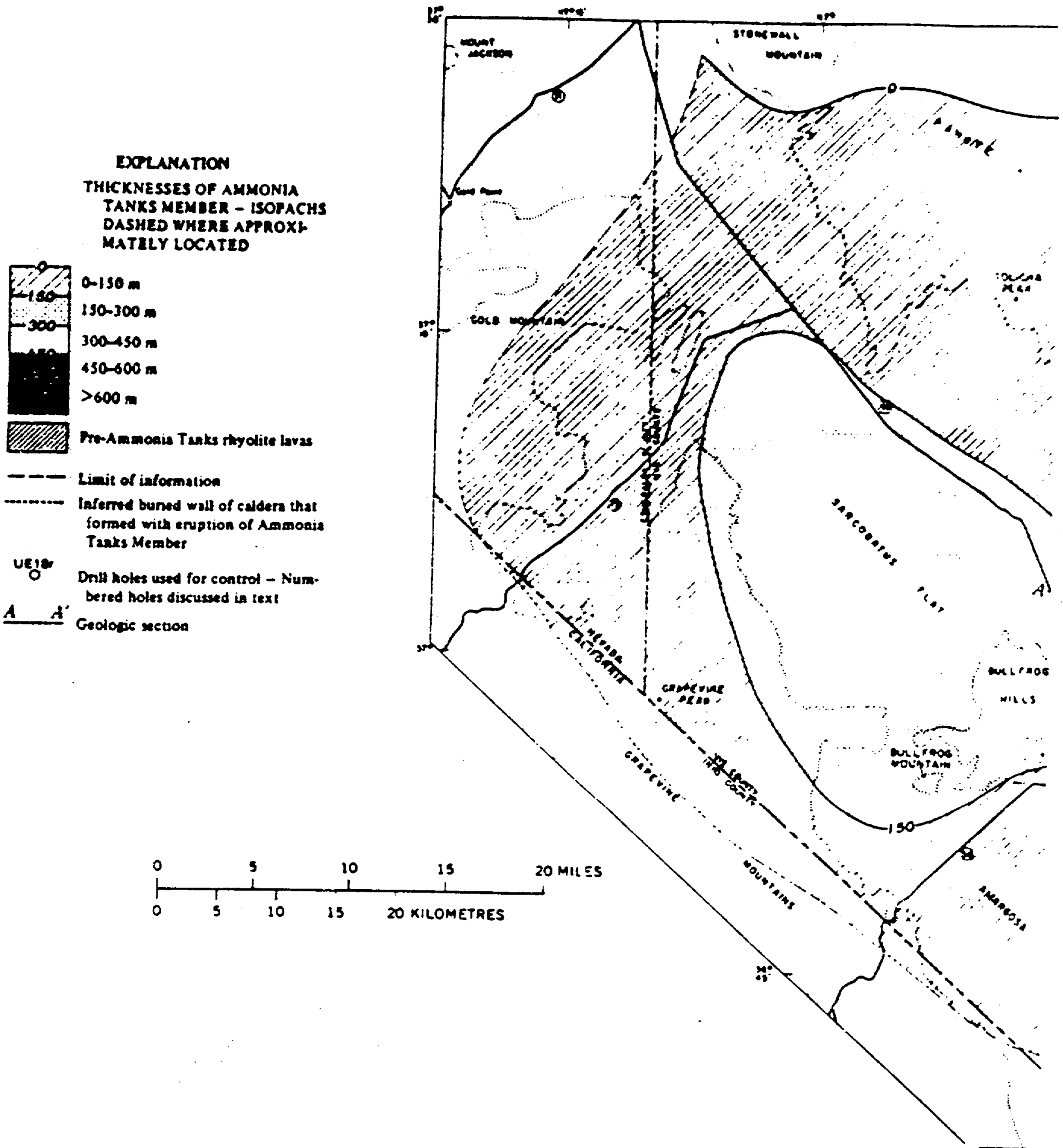
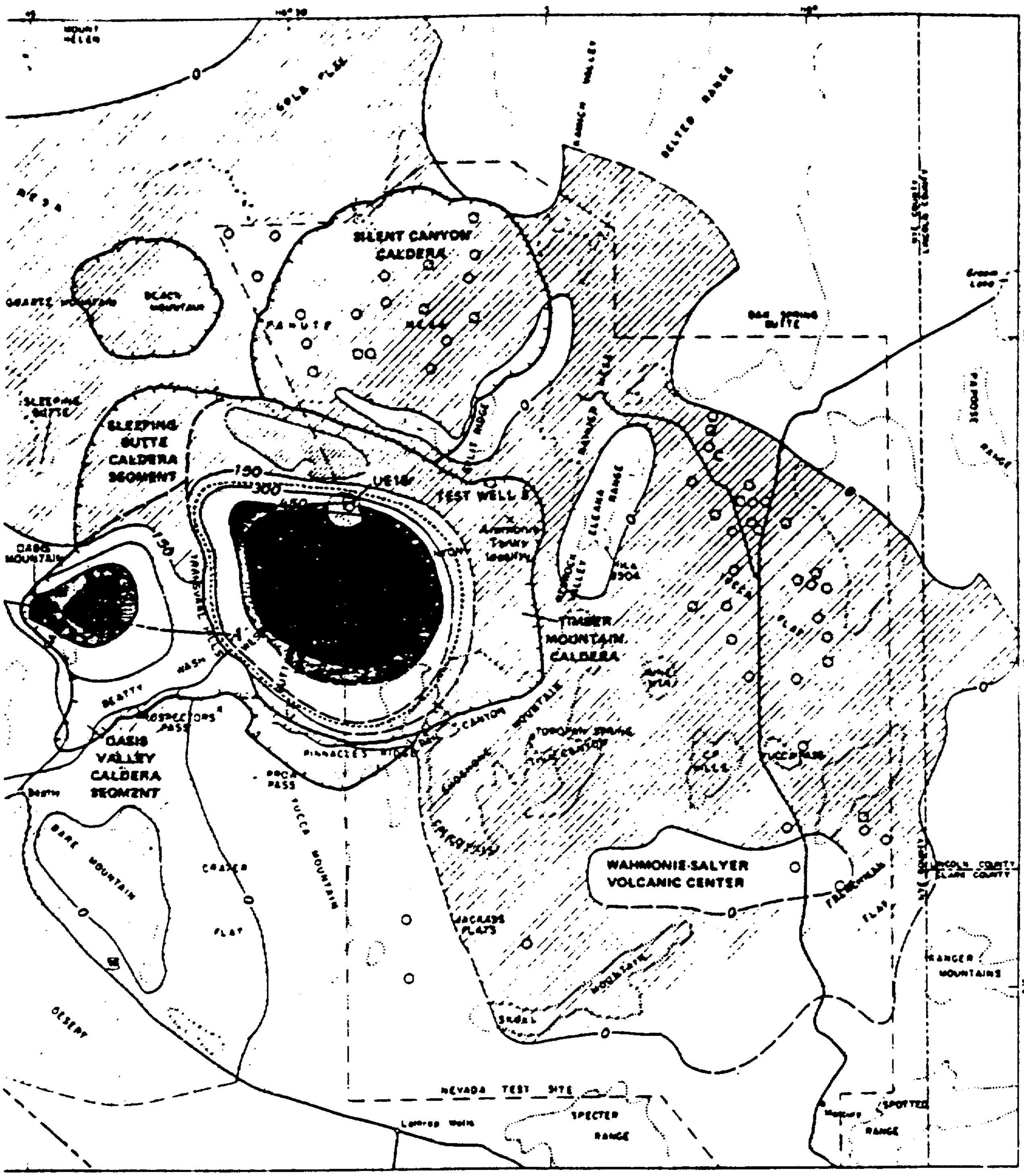


FIGURE 16.—Generalized isopach map of Ammonia Tanks Member of Timber Mountain Tuff, showing great thickness within Timber Moun- shown in

(1,000 ft) thick. An extracaldera section is in the Transvaal Hills (fig. 16; see also fig. 23), where two mapped subunits of the tuff of Camp Transvaal total about 150 m (500 ft) in thickness (Lipman, Quinlivan, and others, 1966) and constitute the lower part of the Ammonia Tanks Member (Byers and others, 1976, section *B–B'*). The upper part of the Ammonia Tanks at this section rests with slight angular discordance but without a complete cooling break



...tain caldera, and associated lava flows that are petrologically sim... to Ammonia Tanks high-silica rhyolite subunits. Geologic cross section figure 23.

...on the lower part of the Ammonia Tanks (Byers and others, 1976, section *B-B'*).

A revised isopach map of the Ammonia Tanks Member (fig. 16; compare with Byers and others, 1968, fig. 5) includes the tuffs of Cat Canyon and Transvaal. The Ammonia Tanks is more than 900 m (3,000 ft) thick beneath the Timber Mountain resurgent dome and slightly more than 450 m (1,500 ft) thick at Oasis

Mountain just inside the wall of the Oasis Valley caldera segment. Elsewhere, the member is generally less than 150 m (500 ft) thick. The total volume of the redefined Ammonia Tanks Member is about 900 km^3 (250 mi^3)—somewhat less than the volume of the Rainier Mesa Member.

The following field and subsurface relations show that the Ammonia Tanks Member outside Timber Mountain caldera is the same cooling unit as the tuff of Cat Canyon on the Timber Mountain resurgent dome inside the caldera. The tuff of Buttonhook Wash overlies the Ammonia Tanks with complete cooling break both on the resurgent dome and on the west rim of Timber Mountain caldera. The stratigraphic succession penetrated in drill hole UE18r (fig. 16) on the buried north flank of the dome includes from top to bottom: the tuff of Cat Canyon (now part of the Ammonia Tanks Member), rhyolite lava, debris flows, and the upper part of the Rainier Mesa Member. This succession is the same as in surface exposures outside the collapse area of the caldera associated with the eruption of the Ammonia Tanks (fig. 16). The Ammonia Tanks in the drill hole is directly correlative with the lower part of the tuff of Cat Canyon in surface exposures several kilometres (a few miles) south on Timber Mountain dome. The contact between the Ammonia Tanks Member and the overlying tuff of Buttonhook Wash is marked by about 10 cm (several inches) of fine ash-fall tuff at exposures within and outside the caldera. The contact zone with the underlying rhyolite lava consists of about a metre (a few feet) of bedded ash-fall tuff, both inside and outside the area of subsidence associated with the eruption of the Ammonia Tanks Member (fig. 16). Moreover, the rhyolite lava is a high-silica rhyolite, petrologically similar to high-silica rhyolite of the Ammonia Tanks (fig. 15). Where the rhyolite lava is missing, the Ammonia Tanks is separated from the Rainier Mesa Member by debris flows and bedded tuff inside the caldera and by not more than 20 m (70 ft) of thick-bedded tuff outside the caldera. The Ammonia Tanks Member, therefore, is tightly bracketed inside and outside the caldera by the underlying units and by the overlying tuff of Buttonhook Wash.

The Ammonia Tanks Member is compositionally far more complex than the Rainier Mesa Member. The Ammonia Tanks is probably a composite sheet as defined by Smith (1960a, p. 812-813), for a local complete cooling break in the extracaldera Ammonia Tanks on Pahute Mesa (Noble and others, 1967) must be represented by one of several partial cooling breaks at the intracaldera section on Timber Mountain dome. The Ammonia Tanks Member is divided into upper and lower parts in order to show fault displacement on the geologic map of the Timber Mountain caldera area (Byers and others, 1976). These two parts can be further subdivided on the basis of composition into quartz latite and (high-silica) rhyolite, as shown in figure 15. The tuff of Cat Canyon (now part of the Ammonia Tanks), originally included six map units on Timber Mountain resurgent dome (Carr and Quinlivan, 1966). In general, our lower quartz latite includes Carr and Quinlivan's units A and B; our lower rhyolite, their units C and D; our upper quartz latite, their unit E; and our upper rhyolite, their unit F; complex intertonguing of these units on the dome, however, makes direct correlation difficult in some localities. Chemical analyses of 25 intracaldera specimens and 23 specimens of extracaldera specimens were made available by W. D. Quinlivan and P. W. Lipman (written commun., 1974).

The four compositional subunits of the Ammonia Tanks Member (fig. 15) are not everywhere present outside the area of Ammonia Tanks subsidence (fig. 16), and are not precisely correlative over the entire extent of the Ammonia Tanks. A few extra lenses of the upper quartz latite intertongue with the upper rhyolite on Timber Mountain dome (Carr and Quinlivan, 1966; 1968, p. 101). In the Dead Horse Flat quadrangle (fig. 2) on eastern Pahute Mesa, Noble, Krushensky, McKay, and Ege (1967) found a complete cooling break between their lower part, a quartz latite, and their main part, consisting of rhyolite overlain by quartz latite. In the area of the extracaldera section on the west rim of Timber Mountain caldera, Lipman, Quinlivan, Carr, and Anderson (1966) mapped a 10° angular unconformity between a lower rhyolitic part, which shows a compound cooling zonatic (their tuff of Camp Transvaal), and an upper part, which consists of rhyolite and quartz latite (their Ammonia Tanks Member). These two parts are seemingly fused together in many places but locally a few centimetres of nonfused bedded tuff separates them (P. W. Lipman, oral commun., 1969). On the east flank of Timber Mountain dome a gentle angular discordance with a partial cooling break occurs between a faulted quartz latite and an overlying unfaulted local high-silica rhyolite, both within the upper part of the Ammonia Tanks (fig. 17).

The lowest compositional subunit (fig. 15), where present, is a quartz latitic vitrophyre with sparse mafic lava xenoliths, especially in the western outcrop area of the Ammonia Tanks (fig. 16). This subunit extends eastward to Shoshone Mountain and eastern Pahute Mesa (fig. 16). In a few localities bordering the tuff dike zone on the eastern flank of Timber Mountain dome, the presumed equivalent subunit is a moderate brown devitrified tuff with conspicuous biotite; the base is not exposed. The overlying subunit, the rhyolite of the lower part (fig. 15), is typically a light-gray high-silica rhyolite with sparse mafic lava xenoliths and wedge-shaped phenocrysts of sphene. On Timber Mountain dome this subunit is compositionally gradational through hundreds of feet downward through low-silica rhyolite into the underlying quartz latite.

Peripheral to Timber Mountain in the northern moat

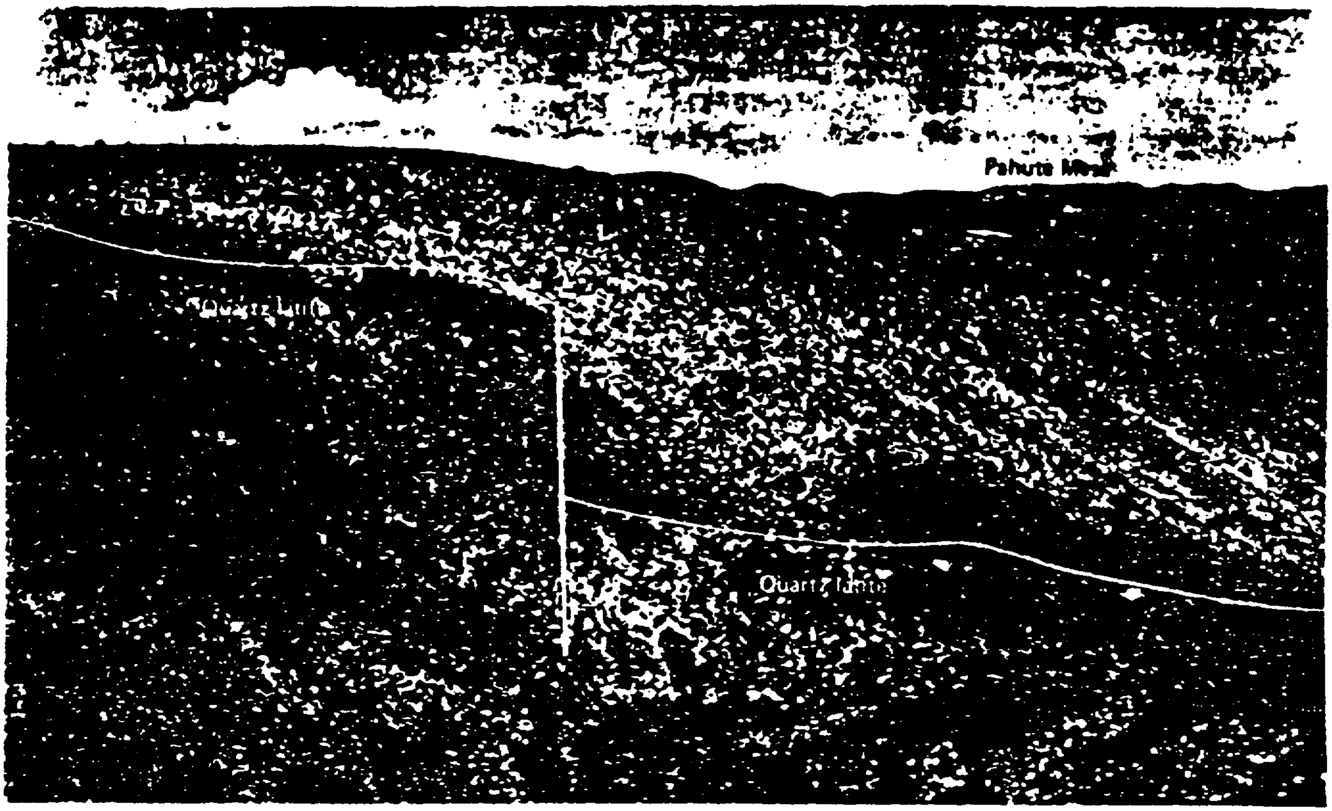


FIGURE 17.—Structural unconformity between uppermost high-silica rhyolite and underlying quartz latite of upper part of Ammonia Tanks Member. North wall of tributary to Brushy Canyon on east flank of Timber Mountain resurgent dome. Timber Mountain caldera wall in far right background. Timber Mountain dome had begun to rise (left or west side of photograph) before uppermost unit involved in doming was extruded, probably through tuff dike zone. The upper (light) unit here has nearly a complete cooling break with the faulted dark welded quartz latite tuff below, whereas a short distance to the west there is only a partial cooling break.

area of Timber Mountain caldera (fig. 16), a thin extracaldera rhyolite, less than 15 m (50 ft) thick, is composed of a pink nonwelded basal zone grading up through a few feet of partly welded gray vitrophyre into an upper light-gray devitrified zone. This rhyolite reappears as the lower subunit of the local main part on eastern Pahute Mesa (Noble and others, 1967). Thin-section modes of this subunit, a high-silica rhyolite, are pooled with the lower rhyolitic subunit of Timber Mountain dome (fig. 15) because the two subunits have similar stratigraphic positions within the Ammonia Tanks. This high-silica rhyolite is overlain by an upper quartz latite (as many as three quartz latites occur at this stratigraphic position on Timber Mountain dome) that can scarcely be distinguished lithologically or petrographically from the lower quartz latite of the Ammonia Tanks (fig. 15). Locally between Ammonia Tanks and test well 8 (fig. 16) this upper quartz latite subunit becomes more mafic than elsewhere, having relatively large phenocrysts, including clinopyroxene, as much as 2.5 mm, and biotite books, as much as 4 mm, which are poikilitic with apatite and zircon.

The uppermost subunit, the upper rhyolite (fig. 15), is found only on the east flank of Timber Mountain dome (fig. 17). The rhyolite is largely white, devitrified, and has spherulitic pumice, characteristic of the vapor phase zone. It is petrographically identical to most of the high-silica rhyolite dikes of the tuff dike zone and contains brown xenoliths of the lower quartz latite subunit, which the dikes intrude.

The average of several K-Ar ages determined on the Ammonia Tanks Member is 11.1 m.y. (Kistler, 1968; Marvin and others, 1970). The Ammonia Tanks Member is equivalent to cooling unit 5 of Cornwall and Kleinhampl (1964, p. J10) in the Bullfrog Hills (fig. 16). Both the extracaldera and intracaldera facies of the Ammonia Tanks have a normal thermal remanent magnetization (G. D. Bath, written commun., 1965).

TUFF OF BUTTONHOOK WASH

The tuff of Buttonhook Wash of Carr and Quinlivan (1966) is a thin compositionally zoned cooling unit above the Ammonia Tanks Member and is here included with the redefined Timber Mountain Tuff. The best exposures

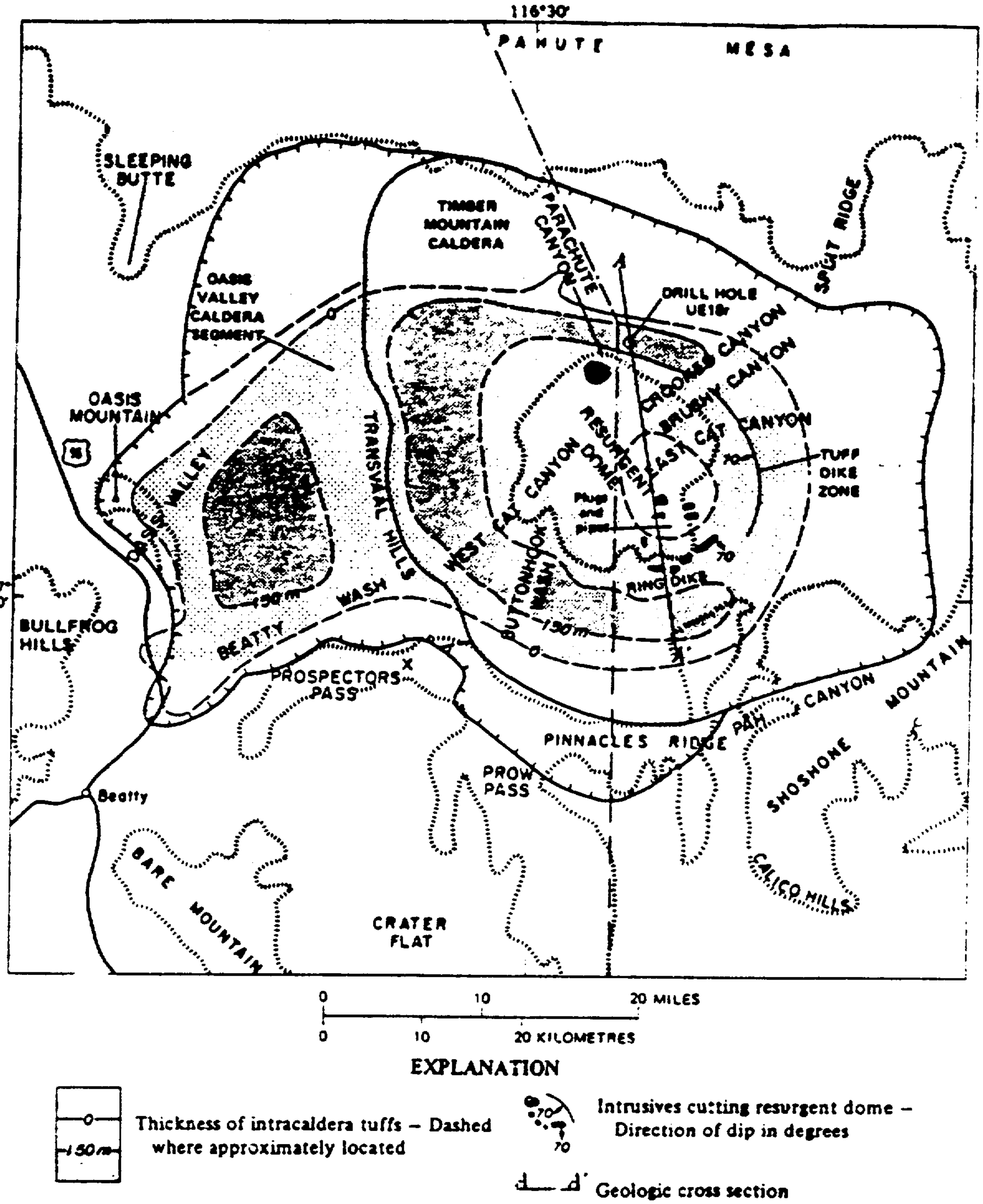


FIGURE 18.—Combined thicknesses of tuffs of Buttonhook Wash and Crooked Canyon and intrusive rocks on Timber Mountain resurgent dome. Tuff of Buttonhook Wash has not been recognized in eastern Timber Mountain caldera and overlying tuffs of Crooked Canyon have not been recognized in the Oasis Valley caldera segment. Geologic cross section shown in figure 22.

are in Buttonhook Wash and in West Cat Canyon, on the southwest flank of Timber Mountain dome (fig. 18).

The distribution of the tuff of Buttonhook Wash together with that of the overlying tuffs of Crooked Canyon is shown in figure 18. Both tuffs are largely confined to the western part of the Timber Mountain-Oasis Valley caldera complex. The tuff of Buttonhook Wash thins over Timber Mountain resurgent lome, mainly by pinchout of its quartz latite caprock (fig. 3). The thickness of the tuff of Buttonhook Wash on the ›stern flank of the dome is about 60 m (200 ft); if the ›ndip thickening is projected under the caldera moat, ›e tuff may thicken to more than 150 m (500 ft). The tuff ›f Buttonhook Wash is found locally above the Ammonia Tanks Member in Oasis Valley and apparently just ›utside the Oasis Valley caldera segment in the eastern Bullfrog Hills, where the tuff may have flowed a short listance against an eroded wall. The tuff of Buttonhook Wash is not present in the intracaldera drill hole UE18r (fig. 18), nor in the eastern and northern moat areas of Timber Mountain caldera.

The tuff of Buttonhook Wash is separated from the ›nderlying Ammonia Tanks Member on Timber Mountain dome by about 10 cm of fine ash-fall tuff, and he lower part is glassy and nonwelded, indicating a brief ›ut complete cooling break. On the west wall of Timber Mountain caldera, the tuff of Buttonhook Wash is also ›eparated from the underlying Ammonia Tanks by about 0 cm of ash-fall tuff. On Timber Mountain dome the tuff ›f Buttonhook Wash is separated from the overlying tuffs ›f Crooked Canyon by a very slight angular uncon-›ormity that is probably related to resurgent doming of Timber Mountain. Less than 60 cm of bedded shard tuff ›eparates the two units.

The tuff of Buttonhook Wash consists of a lower light-gray moderately welded high-silica rhyolite and an upper ›dish- to purplish-brown densely welded quartz latite is locally vitrophyric. The high-silica rhyolite is ›ndistinguishable from high-silica rhyolites of the Ammonia Tanks Member (fig. 15). The quartz latite ›aprock, however, is distinguished from Ammonia Tanks ›uartz latites by (1) plagioclase consistently in excess of ›lkali feldspar phenocrysts (fig. 15), (2) clinopyroxene in ›xcess of biotite, and (3) all phenocrysts rarely exceeding ›.5 mm in contrast to phenocrysts as much as 4.0 mm long ›n the Ammonia Tanks. Sparse hornblende where the tuff ›s not oxidized also distinguishes the tuff of Buttonhook Wash from the upper quartz latite of the Ammonia Tanks. These petrographic features of the quartz latite caprock ›nake the tuff of Buttonhook Wash an excellent strati-graphic marker.

The high SiO_2 content of the quartz latite, nearly 73 percent (fig. 15), is probably due to slight silicification of the devitrified rock.

One K-Ar age of 10.5 m.y., determined on sanidine by Kistler (1968, p. 254), is available from the tuff of Button-hook Wash. Kistler (1968) referred to the unit as "tuff of Cat Canyon, upper cooling unit," a logical designation at that time. This K-Ar age is believed to be slightly young because of slight sericitization of the rock (Marvin and others, 1970, p. 2666). The slight thinning of the tuff onto the Ammonia Tanks Member (average K-Ar age of 11.1 m.y.) over the resurgent dome suggests that resurgent doming had already started before eruption of the tuff of Buttonhook Wash. However, this slight angular dis-cordance is not believed to represent a major time break, for slight angular discordances without a complete cooling break are present within the Ammonia Tanks Member on the east flank of the dome (fig. 17).

TUFFS OF CROOKED CANYON

The tuffs of Crooked Canyon are here included as an uppermost intracaldera unit of the redefined Timber Mountain Tuff (fig. 7) as shown on the map of the Timber Mountain caldera area (Byers and others, 1976). On the east flank of Timber Mountain dome the unit was mapped as tuff of Buttonhook Wash by Carr and Quinlivan (1966) and by Byers, Rogers, Carr, and Luft (1966). The exposed nonwelded distal edges of two ash-flow tuffs constituting the tuffs of Crooked Canyon are each less than 8 m (25 ft) thick where they onlap the northeast flank of the dome (fig. 18) in Crooked Canyon. Downdip in the subsurface off the northern flank of Timber Mountain, the tuffs thicken rapidly to more than 250 m (800 ft) toward the outer edge of the caldera and become partly welded; they were penetrated in the interval from 335 to 593 m (1,100 to 1,945 ft) in drill hole UE18r in the northern moat of the caldera (figs. 3, 18). The total thickness of the upper tuff in the drill hole is about 180 m (600 ft); the lower tuff, 75 m (245 ft) thick, was not cored. The great increase in thickness, from the exposed flank of Timber Mountain dome outward to drill hole UE18r, indicates that the tuffs of Crooked Canyon were emplaced after the resurgent central dome was well advanced.

The tuffs of Crooked Canyon overlie the tuff of Button-hook Wash or the Ammonia Tanks Member with a minor angular unconformity (fig. 3) and overlie the tuff of Buttonhook Wash in the central graben of the Timber Mountain resurgent dome. The contact zone between the tuffs of Crooked Canyon and the underlying Ammonia Tanks Member or tuff of Buttonhook Wash consists of 1 m or less of uniformly finegrained ash-fall shard tuff; more-over, the contact zone between the two ash-flow tuffs of Crooked Canyon contains 10–60 cm of fine ash-fall tuff, in contrast to as much as 18 m of variegated thin-bedded fine to coarse ash-fall tuff separating the tuffs of Crooked Canyon from the overlying post-Timber Mountain cooling units of the caldera fill (Byers and others, 1976).

No compositional zoning in either of the tuffs of Crooked Canyon is apparent. The lower tuff is a simple nonwelded to moderately welded cooling unit of uniform rhyolitic composition, almost everywhere devitrified and pinkish to purplish gray, except at the distal edges flanking Timber Mountain dome. It contains fewer and smaller phenocrysts, with slightly more mafic pheno-crysts than the high-silica rhyolite in the upper part of the Ammonia Tanks (fig. 15). Near the tuff dike zone, it contains distinctive brown xenoliths characteristic of the lower quartz latite of the Ammonia Tanks Member in the tuff dike zone. A few thin tuff dikes (fig. 18), identical in composition to the lower tuff, also contain these brown xenoliths, indicating the probable source of the tuff (see footnote description in Byers and others, 1966).

The upper tuff is orange brown, glassy, and nonwelded near its pinchout on the northeast flank of Timber Mountain dome and likewise contains brown xenoliths from the lower quartz latite of the Ammonia Tanks in the tuffdike zone, suggesting a possible source similar to that of the lower tuff. The upper tuff contains, in addition, diagnostic phenocryst-poor glass xenoliths and phenocryst-rich pumice lumps. In drill hole UE18r, the upper tuff is partly welded and, except for the glass xenoliths and its stratigraphic position above the lower tuff and the Ammonia Tanks, is almost indistinguishable petrographically from similar parts of the Ammonia Tanks (fig. 15).

The K-Ar age of the tuffs of Crooked Canyon is bracketed by the 10.5-m.y. age of the tuff of Buttonhook Wash and by the K-Ar age of 9.5 m.y. on the overlying tuff of Cutoff Road (Lipman, Quinlivan, and others, 1966; tuff of the caldera fill of Kistler, 1968, p. 254). The 10.5-m.y. K-Ar age of the tuff of Buttonhook Wash, however, is probably slightly young because of alteration of the rock (Marvin and others, 1970, p. 2666). More likely the K-Ar age of the tuffs of Crooked Canyon is close to 11 m.y., as suggested by the stratigraphic relations: less than 60 cm of ash-fall occurs between the tuffs of Crooked Canyon and the underlying units of the Timber Mountain Tuff, whereas about 18 m (60 ft) of thin-bedded ash-fall tuff separates the overlying, 9.5-m.y., unit from the tuffs of Crooked Canyon near their pinchout on the east flank of Timber Mountain dome. On the west side of the Oasis Valley caldera segment, about 300 m (1,000 ft) of volcanic rocks, comprising bedded tuff, three ash-flow tuff cooling units, and a lava flow, occurs within this same stratigraphic interval in caldera fill (fig. 23). Moreover, the cooling units within the 300-m caldera-fill interval are petrologically dissimilar from the underlying quartz-bearing tuffs of Crooked Canyon and other units of the Timber Mountain Tuff as herein defined. From this stratigraphic and petrologic evidence, the tuffs of Crooked Canyon apparently are close in K-Ar age to the Ammonia Tanks Member, possibly about 11 m.y.

The petrologic and inferred close-time relations between the upper units of the Timber Mountain Tuff are consistent with the relatively small volume of the tuffs of Crooked Canyon, their lack of compositional zoning, their generally nonwelded to partly welded character, and their stratigraphic position as the youngest tuffs of the Timber mountain eruptive sequence. All these features indicate a marked decrease in the eruptive activity of the Timber Mountain magma chamber (fig. 3) following voluminous eruptions of the Rainier Mesa and Ammonia Tanks Members and the onset of resurgent doming of Timber Mountain.

DEBRIS FLOWS

The term "debris flows" as used here designates clastic deposits emplaced by rapid flowage of coarse and fine detritus. Such deposits are exposed within Timber Mountain caldera near the eastern and northern walls and within the Oasis Valley caldera segment in the Transvaal Hills and near the west wall just west of Oasis Mountain (figs. 14, 16). The unit overlies and locally intertongues with the uppermost part of the Rainier Mesa Member in the vicinity of test well 8 and in Beatty Wash where it crosses the southern end of the Transvaal Hills (fig. 14) but is not considered part of the redefined Timber Mountain Tuff. The debris flows underlie the Ammonia Tanks Member and pre-Ammonia Tanks rhyolite lava in drill hole UE18r (fig. 3). The unit has not been found outside Timber Mountain caldera or the Oasis Valley caldera segment.

The debris flows are best exposed on the east side of the Timber Mountain caldera south of test well 8 (fig. 16) where the unit consists mostly of blocks of welded tuff as much as 6 m (20 ft) long in a yellowish-gray to grayish-orange tuffaceous matrix. The lower part of the deposit is nonsorted and nonstratified and apparently represents a single debris flow, but the highest part of the unit contains well-sorted and bedded lenses of reworked tuff which separate several thinner flows. These thinner flows contain more fine tuffaceous matrix with fewer angular cobbles than does the single flow, and the thinner flows may have been emplaced as successive mudflows. All rock types present in the caldera wall, including the lower rhyolitic subunit of the Rainier Mesa Member, are present in the coarse detritus. Densely welded tuff of the Paintbrush Tuff, Grouse Canyon Member of the Belted Range Tuff, and rhyolite of the lower part of the Rainier Mesa Member occur as blocks in the debris flows along the east wall of Timber Mountain caldera; fragments of rhyolite lavas predominate inside the north wall where pre- and post-Tiva Canyon rhyolite lavas are exposed. In the southern part of the Transvaal Hills, fragments of intracauldron Paintbrush Tuff are most abundant and indicate a source from the Claim Canyon cauldron segment. The debris flows are exposed in places inside the Oasis Valley caldera segment west and south of Oasis Mountain and contain an assemblage of blocks similar to those of the debris flows inside Timber Mountain caldera.

Debris flows related to caldera collapse were penetrated in drill hole UE18r from a depth of 1,183 to 1,442 m (3,880 to 4,730 ft). They are overlain by pre-Ammonia Tanks rhyolite lava and underlain by the Rainier Mesa Member. Blocks many feet across are contained in a tuffaceous matrix. Most of the debris is welded tuff of the Paintbrush Tuff, but rhyolite lava intercalated with Paintbrush and blocks of rhyolitic Rainier Mesa are also present. No rocks older than Paintbrush Tuff were identified.

The stratigraphic position of the debris flows, their intertonguing relation with the uppermost Rainier Mesa quartz latitic tuff, the presence of rhyolitic blocks from the lower part of the Rainier Mesa, and finally the location of the exposed ends of the flows just within caldera walls all indicate that the bulk of the debris flows were generated catastrophically within a short period of time as a result of caldera collapse related to the eruption of the Rainier Mesa Member. The debris flows contain assorted discrete blocks of the lower rhyolitic subunit of the Rainier Mesa, indicating the presence of already solidified Rainier Mesa in the caldera wall. This relation further suggests that the Rainier Mesa Member is a composite ash-flow sheet in Smith's (1960a) terminology.

LAVAS PETROLOGICALLY RELATED TO TIMBER MOUNTAIN TUFF

PRE-RAINIER MESA LAVAS

Lava flows underlie the Rainier Mesa and Ammonia Tanks Members. The lava flow immediately under each member is petrographically similar to the member which overlies it. The pre-Rainier Mesa lavas (fig. 14) are divisible into two petrographic types: low-silica rhyolite lavas with sphene—the rhyolite of Windy Wash of Christiansen and Lipman (1965)—and high-silica rhyolite lavas without sphene and with few mafic phenocrysts, petrographically and chemically like the high-silica rhyolitic tuff of the Rainier Mesa Member (fig. 15). The stratigraphic relations between these two rhyolites are not certain, but the fact that the high-silica rhyolite is petrographically more similar to the overlying Rainier Mesa Member than to the rhyolite of Windy Wash suggests that the high-silica lava postdates the rhyolite of Windy Wash. Moreover, the rhyolite of Windy Wash bears some petrologic affinity to the underlying Tiva Canyon Member of the Paintbrush Tuff and to the post-Tiva Canyon rhyolite lavas, mainly in sphene content and in the composition of opaque iron-titanium oxides (Lipman, 1971). The rhyolite lavas of Windy Wash commonly have a dark basal vitrophyre overlain by a pale-red devitrified interior. Feeder dikes of these flows are exposed as radial dikes in the south wall of Timber Mountain caldera (Byers and others, 1976), and one dike can actually be traced into the flow on the rim of the caldera. A rhyolite lava identical in lithology and chemistry (W. D. Quinlivan and P. W. Lipman, written commun., 1974) to the rhyolite of Windy Wash was penetrated in two drill holes in Silent Canyon caldera (fig. 14). This lava was called "quartz-rich lava of Scrugham Peak quadrangle" by Byers and Cummings (1967) and by Orkild, Sargent, and Snyder (1969; see composite diagram of their usage in fig. 7). The nearly identical thin-section modes of flows in these two areas on opposite sides of Timber Mountain caldera are shown in figure 19. The close similarity in composition of the lavas in these two areas suggests that the lavas were erupted at about the same time from the same compositional layer in the underlying magma chamber.

The high-silica rhyolite lava crops out on the southwest side of the Timber Mountain–Oasis Valley caldera complex in the vicinity of Beatty (fig. 14). It has a typical glassy envelope with a light-gray devitrified interior. The lava is rather sparsely porphyritic and contains about equal numbers of quartz and sanidine phenocrysts; the sanidine has cryptoperthite(?) reaction rims similar to

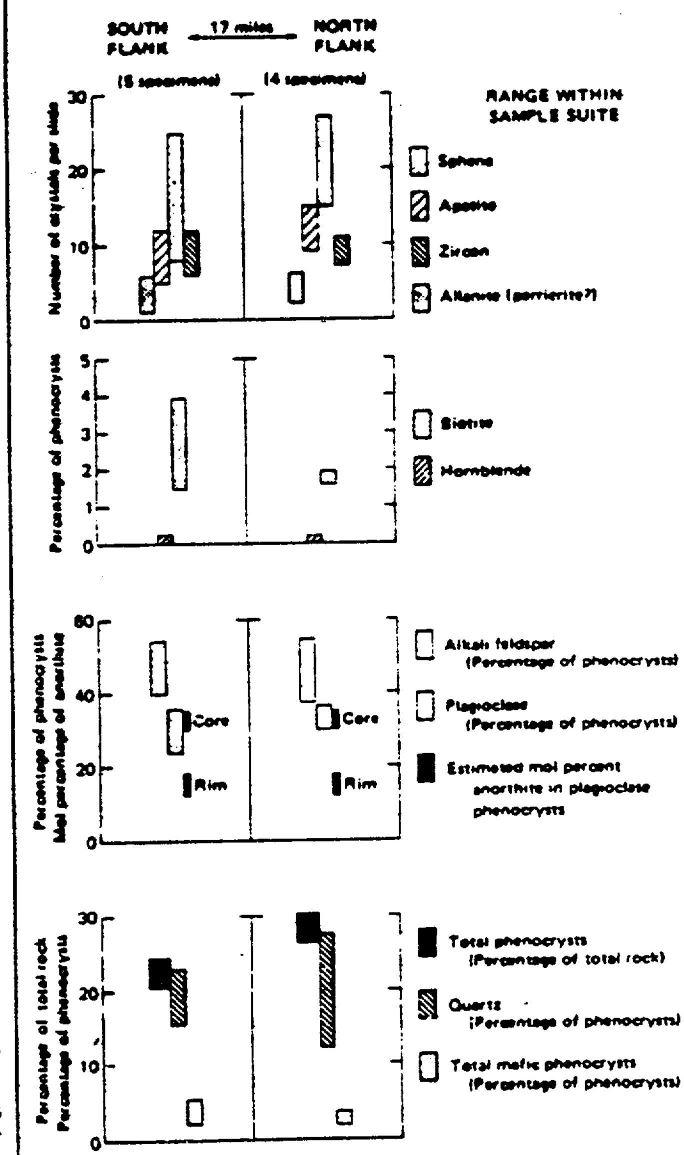


FIGURE 19.—Phenocryst mineralogy of rhyolite lava of Windy Wash (pre-Rainier Mesa lavas) on opposite flanks of Timber Mountain caldera. Lava flow on north flank penetrated in drill holes (figs. 5, 14).

those of sanidine phenocrysts in the Rainier Mesa Member.

The pre-Rainier Mesa rhyolite lavas correlate in part with "rhyolite flows and intrusives" of Cornwall and Kleinhampl (1964, p. J11; pl. 4). A K-Ar age determined on the high-silica rhyolite under the Rainier Mesa Member east of Beatty is 11.3 m.y. (Kistler, 1968, p. 255), the same age as the Rainier Mesa Member (Marvin and others, 1970, p. 2261).

PRE-AMMONIA TANKS LAVAS IN TIMBER MOUNTAIN CALDERA MOAT

The pre-Ammonia Tanks lavas are exposed near the north and southwest walls of Timber Mountain caldera (fig. 16) beneath thin glassy exposures of the Ammonia Tanks Member. These outcrops are in the outer annular moat which subsided during the eruption of the Rainier Mesa Member but which was not affected by collapse related to the eruption of the Ammonia Tanks Member (fig. 16). The lavas in the northern moat area of Timber Mountain caldera were called "rhyolite lavas of Timber Mountain caldera moat" on the map of the Scrugham Peak quadrangle (Byers and Cummings, 1967; fig. 2). In addition to the surface exposures, a lava flow was penetrated in the interval from 1,082 to 1,183 m (3,550 to 3,880 ft) in drill hole UE18r (figs. 3, 16) between the Ammonia Tanks Member and the underlying debris flows which partly filled the collapse area related to eruption of the Rainier Mesa Member.

The pre-Ammonia Tanks lavas are glassy in the lower parts and have subjacent locally fused bedded tuff. The interiors of the flows are purplish gray laminated to light gray microcrystalline with conspicuous quartz phenocrysts. The upper parts are light gray, porous, glassy, and commonly brecciated, typical of most rhyolite lavas. The lavas contain sphene and are petrochemically (W. D. Quinlivan and P. W. Lipman, written commun., 1974) generally similar to rhyolitic parts of the Ammonia Tanks but contain fewer phenocrysts. Thin-section modes (fig. 15) of the northern lava are the same as those of the southern lava (fig. 16), indicating a close magmatic and temporal relationship similar to that between the northern and southern bodies of the rhyolite of Windy Wash of pre-Rainier Mesa age (fig. 19) already described. The cycle consisting of eruption of lava followed by eruption of tuff petrologically similar to the lava appears to have been repeated.

A core of the uppermost zeolitized brecciated part of pre-Ammonia Tanks rhyolite lava from drill hole UE18r contained about 1 percent phenocrysts, consisting of sparse quartz, sanidine, and 1 phenocryst of sphene. This nearly aphyric lava may have been extruded at a slightly different time than the lavas exposed in the northern and southern moat areas of Timber Mountain caldera, but the sample may not be truly representative.

The age of the pre-Ammonia Tanks rhyolite lavas is bracketed by K-Ar ages of 11.3 m.y., determined on the Rainier Mesa Member (Marvin and others, 1970), and 11.1 m.y., determined on specimens of the Ammonia Tanks Member of the Timber Mountain Tuff (Kistler, 1968). The thermal remanent magnetization is reverse like that of the underlying Rainier Mesa but unlike that of the overlying Ammonia Tanks Member (G. D. Bath, written commun., 1965).

INTRUSIVE ROCKS AND RELATION TO RESURGENT DOMING

Intrusive rocks on Timber Mountain resurgent dome that are largely post-Ammonia Tanks comprise an outer tuff-dike zone, an inner microgranite-porphyry ring dike (Carr, 1964, p. B17), and intrusive rhyolite mainly in the central part of the dome (fig. 18). These intrusive rocks are petrologically closely similar to either high-silica rhyolitic or quartz latitic subunits of the Timber Mountain Tuff; these similarities, together with position and field relations of the intrusive rocks on Timber Mountain resurgent dome, imply a close genetic relation to the Timber Mountain Tuff. Presumably the tuffs, the related lavas, and the intrusive masses were derived from the same underlying magma that resurged and caused the doming of Timber Mountain.

The tuff dike zone crops out on the outer eastern flank of the Timber Mountain dome and parallel to it (fig. 18). The dikes dip steeply inward toward the center of Timber Mountain (fig. 20). They are mostly high-silica rhyolite in composition and range in thickness from 0 to 8 m (26 ft). They intrude a distinctive brown devitrified facies of lower quartz latite of the Ammonia Tanks in an area about 150 m (500 ft) wide. Some dikes appear to be feeders to the uppermost high-silica rhyolite subunit of the Ammonia Tanks, for this subunit is not only petrographically identical with these dikes (fig. 21), but also contains the same distinctive brown xenoliths of the lower quartz latite subunit of the Ammonia Tanks. These dikes have a sharp contact with the Ammonia Tanks but show no evidence of chilling, indicating that the Ammonia Tanks was still hot at the time of intrusion.

A few dikes are petrologically similar to the two tuffs of Crooked Canyon, which also contain xenoliths of Ammonia Tanks quartz latite. The slightly finer grain size of these dikes, at the contact indicates chilling and suggests that the dikes were intruded after the Ammonia Tanks had cooled somewhat. Although it is not possible to distinguish petrographically between dikes that may have been feeders for either the lower or upper tuff of the tuffs of Crooked Canyon, the presence of xenoliths in the tuffs indicates that their vent source was probably the tuff dike zone. No modal ranges of these dikes are shown in figure 21, because the feldspar phenocrysts are too altered to allow distinguishing sanidine and plagioclase.

FIGURE 20.—Rhyolitic tuff dike cuts basal quartz latite of Ammonia Tanks Member and dips inward (westerly) along arcuate zone around the east flank of Timber Mountain dome. Dikes were probably feeders for uppermost high-silica rhyolite of Ammonia Tanks and tuffs of Crooked Canyon. Flattened pumice (P, barely visible) and biotite foliation in quartz latite host rock are parallel to walls of dike. Note fragments of dark quartz latite tuff in dike and white (recrystallized) nonflattened pumice in quartz latite host rock. Exposure in Brushy Canyon (fig. 18).

The microgranite porphyry ring dike consists of several alined discordant bodies (fig. 18) that intrude the lower part of the Ammonia Tanks Member. The dike is in an inner ring-fracture zone closer than the tuff dike zone to the apex of the Timber Mountain dome. Here the Ammonia Tanks is extremely thick (fig. 16) and may have extended as much as 600 m (2,000 ft) above the highest level penetrated by the ring dike. The contacts of the various bodies are abrupt, and the porphyry shows no change in texture or mineralogy at the borders. The lack of chilled borders suggests that the Ammonia Tanks host rock was still hot when the dikes were emplaced. Several of the dikes and irregular bodies broaden downward, presumably to connect at depth. The ring-dike system is generally parallel to an arcuate fault zone, a short distance to the southeast. Both the arcuate fault zone and also the ring dike dip steeply southeast (fig. 18), away from the central part of Timber Mountain resurgent dome. The intrusion of the porphyry dike probably accompanied the resurgent doming of Timber Mountain (Carr, 1964; Carr and Quinlivan, 1968, p. 103–104).

The microgranite porphyry is nearly uniform in general appearance, texture, and color; small bodies differ only slightly in texture from the largest. It is medium- to light-gray nonfoliated fairly homogeneous porphyritic rock containing about 50 percent phenocrysts of abundant feldspar as much as 1 cm across, minor biotite, and clinopyroxene (fig. 21) in a very finely granular groundmass. Quartz and sphene phenocrysts are absent. The large feldspar phenocrysts consist of small plagioclase cores less than 3 mm in size, rimmed by a thick jacket of alkali feldspar. The groundmass is largely quartz and alkali feldspar, 0.1 to 0.2 mm in size and partly as granophyric intergrowths. The microgranite porphyry is almost chemically identical with the more mafic quartz latitic upper part of the Ammonia Tanks that contains 66–68 percent silica (W. D. Quinlivan and P. W. Lipman, written commun., 1974). The microgranite porphyry, however, had attained a more advanced stage of crystallization, as evidenced by (1) larger and slightly more abundant phenocrysts (fig. 21) and (2) more abundant alkali feldspar in the form of thick outer jackets enclosing plagioclase in the larger phenocrysts. Mafic quartz latites of the Ammonia Tanks and also the microgranite porphyry contain little if any quartz and sphene. The name "microgranite porphyry" was applied to these rocks prior to obtaining chemical analyses (W. D. Quinlivan and P. W. Lipman, written commun., 1974).

In addition to microgranite porphyry dikes, pipelike and pluglike bodies of rhyolite, and probably quartz latite, intrude the upper part of the Ammonia Tanks Member on Timber Mountain dome. Contact zones are commonly glassy and gradational through a horizontal zone of as much as 90 m (300 ft); considerable mixing and remobilization occurred between the glassy intrusives and the tuff subunits of the Ammonia Tanks. A few intrusives are coextensive with small extrusive domes that rest on, and show a complete cooling break from, the upper part of the Ammonia Tanks. Two petrologic types in different structural settings on the dome are included in the intrusive rhyolite. The rhyolite of Parachute Canyon (fig. 18), probably a quartz latite, is on the north flank of the dome near the inner ring-fracture zone, which is not well exposed here. In contrast, the rhyolite lavas of East Cat Canyon are composed of high-silica rhyolite, and were extruded from vents along faults of the central graben of the resurgent dome.

The rhyolite of Parachute Canyon is a plug dome, as evidenced by vertical foliation near steep contacts. Vertical foliation is lacking in areas where the rhyolite reached the surface and flowed onto the upper part of the Ammonia Tanks Member. The interior of the body is light gray and porphyritic, and contains abundant small lithophysae, but it is encircled by a darker, finer grained border zone that is locally glassy, particularly on its northwest side where it apparently flowed onto the Ammonia Tanks. The border zone appears to consist of a few hundred metres of

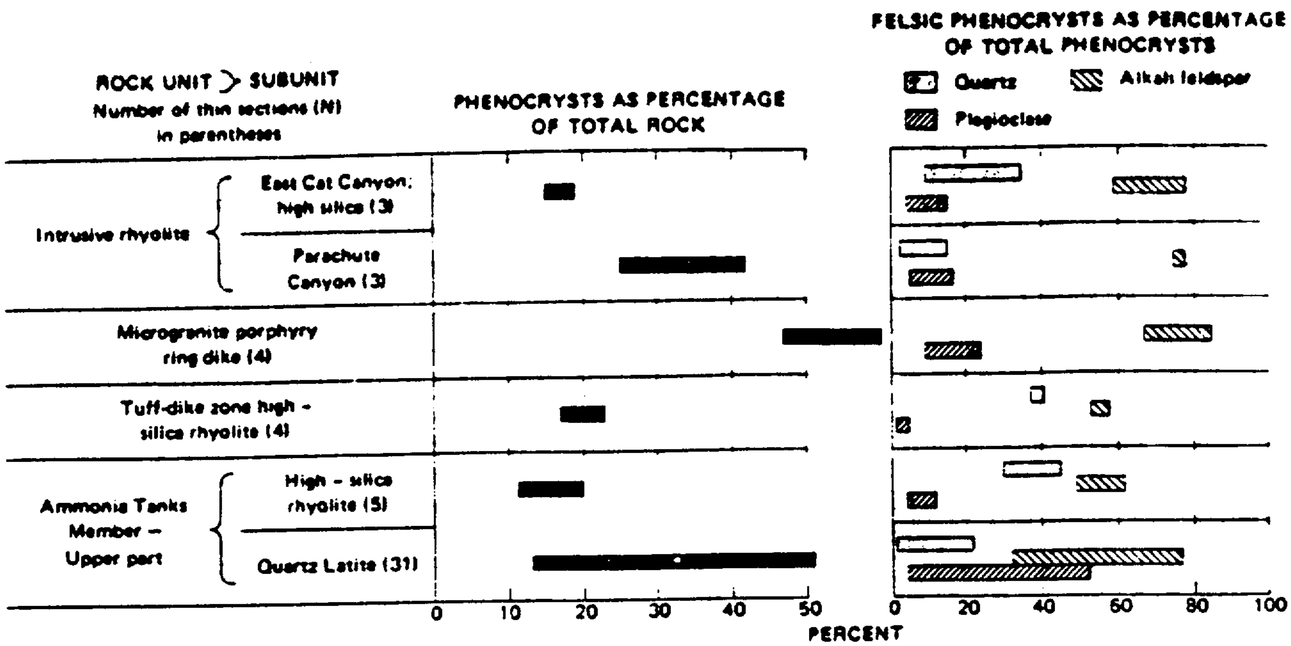


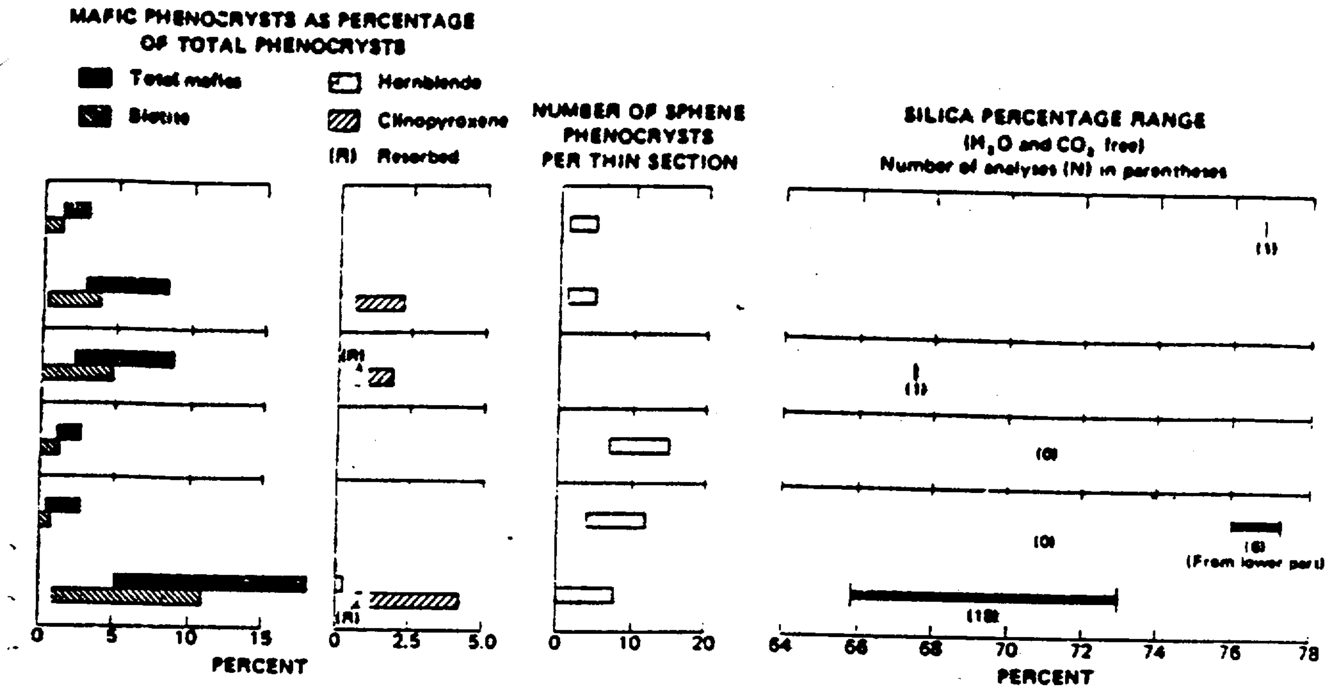
FIGURE 21.—Modal and silica ranges of intrusive rocks on Timber Mountain compared with ranges of high-silica rhyolite and quartz latite Member of Timber Mountain Tuff. Silica analyses from

Ammonia Tanks near the apex of the Timber Mountain resurgent dome (fig. 18). The pipes are localized along the faulted margin of a northwest-trending central graben, described by Carr and Quinlivan (1968, p. 105). The central parts of the pipes are light gray and devitrified, whereas the border zones are generally glassy or finely spherulitic. In a few places a crystallized transitional border zone as much as 15 m (50 ft) wide contains alternating bands of rhyolite having different phenocryst contents and probably represents a zone of intermixed intrusive high-silica rhyolite and remobilized quartz latite wallrock of the Ammonia Tanks Member. The modal range of three specimens and the silica content of 76.8 percent approach the composition of a typical high-silica rhyolite of the Ammonia Tanks Member (fig. 21).

The inferred relations among the Ammonia Tanks Member in the Timber Mountain resurgent dome, the petrologically related intrusives, and an inferred underlying compositionally zoned magma chamber are shown in figure 22. The two-layer compositional zoning of the upper part of a large magma chamber is based on models suggested by Quinlivan and Lipman (1965), by Lipman, Christiansen, and O'Connor (1966), and by Smith and Bailey (1966). The inward-dipping tuff dikes formed from high-silica rhyolite magma near the apical part of the magma chamber and are somewhat analogous to cone sheets (Anderson, 1936). The rhyolite intrusives of East mixed flow-banded rhyolite and probably fused mobilized quartz latite wallrock of the upper part of the Ammonia Tanks Member. Parts of the intrusive mass are quartz rich, and others are quartz poor, thus indicating a pronounced internal compositional variation that may reflect composite intrusions.

The porphyritic central part of rhyolite of Parachute Canyon, whose mode is shown in figure 21, is more likely a quartz latite. Phenocrysts of alkali feldspar, as much as 8 mm across, enclose cores of subordinate plagioclase, with minor embayed quartz and biotite, all in a microcrystalline groundmass. This central part petrographically shows a striking textural and modal similarity to the microgranite porphyry dike (fig. 21), except for smaller groundmass crystals and somewhat fewer phenocrysts, and it probably represents a more chilled fine-grained upward extension of similar microgranite porphyry at depth. The quartz and sphene in the central part may represent mixture at one stage or another of chilled rhyolitic tuff of the Ammonia Tanks Member or of similar magma composition. The Parachute Canyon vent is also located near the inner ring-fracture zone on the flank of the Timber Mountain dome, a structural position similar to that of the porphyry ring dike on the south side (fig. 18).

Pipelike intrusives of high-silica rhyolite, one grading upward into a plug dome, cut the upper part of the



subunits of upper part of Ammonia Tanks Member. Age relations uncertain except that intrusive rocks generally postdate Ammonia Tanks W. D. Quinlivan and P. W. Lipman (written commun., 1974).

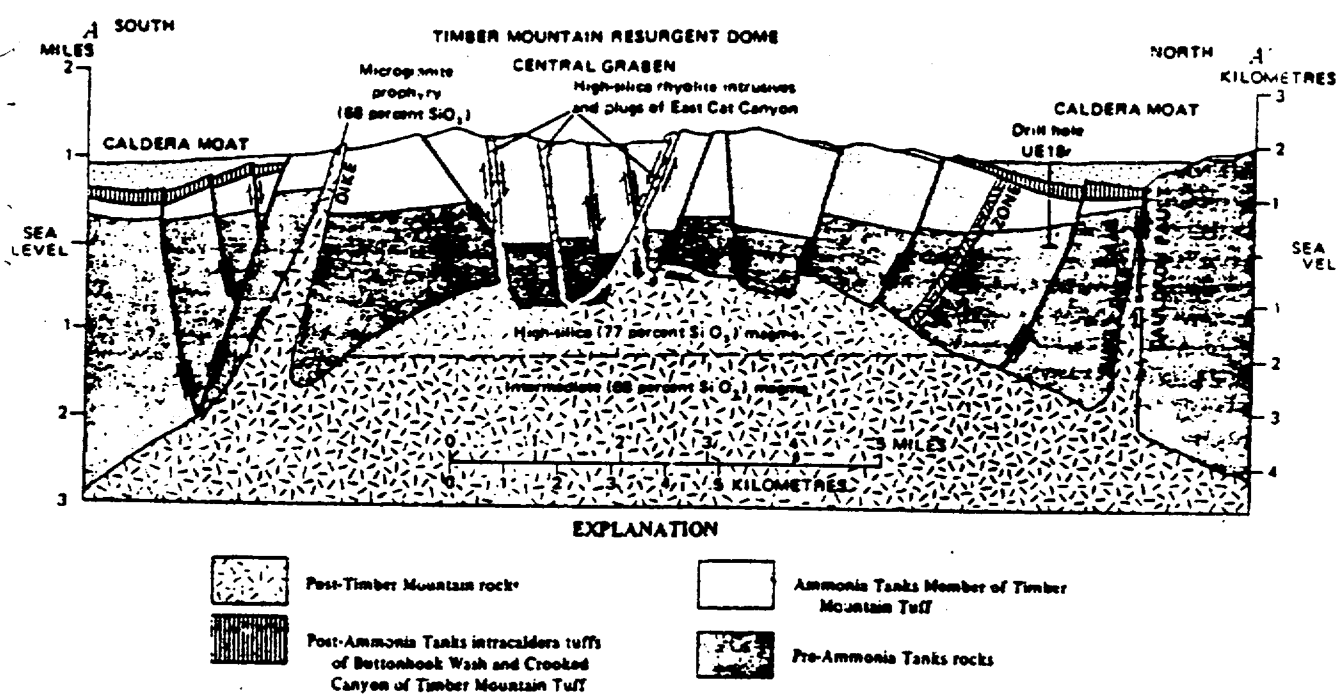


FIGURE 22.—Generalized interpretive section across Timber Mountain resurgent dome, showing inferred relations between compositionally zoned magmatic source of Timber Mountain Tuff and related intrusives cutting Timber Mountain resurgent dome. Line of section shown in figure 18.

Cat Canyon, localized along marginal faults of the central graben, also formed from the high-silica rhyolite in the upper part of the magma chamber. The outward-dipping microgranite porphyry ring dike formed from quartz latitic magma, which averaged about 68 percent silica, and lay below the high-silica rhyolite interface.

This idealized model of the magma chamber would probably be attained prior to and reestablished a short time after the voluminous extrusion of the Ammonia Tanks Member with its complex compositional gradations of high-silica rhyolite and quartz latite. Intermixing of these two compositions within the Ammonia Tanks Member inside the Timber Mountain caldera indicates disturbance of the interface (fig. 22) and probably the extrusion of the Ammonia Tanks Member from many vents, as originally suggested by Quinlivan and Lipman (1965).

CALDERA COLLAPSES RELATED TO ERUPTIONS OF RAINIER MESA AND AMMONIA TANKS MEMBERS

Discussion of areas of collapse related to eruptions of the Rainier Mesa and Ammonia Tanks Members of the Timber Mountain Tuff has been deferred until all the petrologically related quartzose igneous rocks that are defined as belonging to the Timber Mountain caldera center have been described. Timber Mountain caldera, as shown in figure 1 and other illustrations of this report, was originally defined not on the basis of its extrusive products but as a volcano-topographic feature in the Williams (1941) sense. The perspective diagram (see frontispiece) illustrates the extent of a subcircular caldera wall enclosing a moatlike annular area surrounding the central dome. Only in the northwestern part, where Thirsty Canyon has been incised, is the caldera wall lacking. These topographic features, indicative of a caldera and central resurgent dome, were recognized by R. L. Smith as early as 1960, and the name Timber Mountain was applied to the caldera and resurgent dome after the topographically prominent central mountain. There are, however, not one but two voluminous coextensive ash-flow sheets, petrologically similar and erupted within a few hundred thousand years of one another, that are distributed peripherally to Timber Mountain caldera. Did Timber Mountain caldera as defined topographically result as a collapse feature related mainly to eruption of the Rainier Mesa Member, or is it a composite caldera resulting from two or more eruptions of Timber Mountain Tuff, or, still a third possibility, did other adjacent areas subside, producing a volcano-tectonic depression, during eruption of the members? These alternatives and their possible combinations are considered next.

The known areal extents of both the Rainier Mesa and Ammonia Tanks Members are closely similar, as a comparison of figures 14 and 16 will show. The extracaldera thickness of the Rainier Mesa Member, however, is locally two to three times thicker than the Ammonia Tanks in former topographic depressions such as Silent Canyon caldera; elsewhere the Rainier Mesa Member is generally 50–100 percent thicker than the Ammonia Tanks (Byers and others, 1968, p. 91 and 93). Inasmuch as the intracaldera thickness of the Rainier Mesa Member is not known, only a minimum volume of 1,200 km^3 (300 mi^3) of the Rainier Mesa Member can be inferred, compared with a more accurately known total volume of 900 km^3 (230 mi^3) of the Ammonia Tanks. The intracaldera thickness of the Rainier Mesa might well be twice that of the Ammonia Tanks, and the total volume of the Rainier Mesa Member might well be nearly twice that of the Ammonia Tanks. Obviously, the approach of comparing the extracaldera volumes of the members with the areas and volumes of collapse is fraught with many unknowns, including the intracaldera thickness of the Rainier Mesa. A further complicating factor is the possibility that an inner Ammonia Tanks ring-fracture zone may have also been loci for some collapse along an inner zone during eruption of the Rainier Mesa Member. As a first approach, however, it seems likely that the area of collapse related to the Rainier Mesa eruption would be somewhat larger than that related to the Ammonia Tanks eruption. Fortunately, more direct evidence bearing on this problem is available.

The area of collapse related to the eruption of the Ammonia Tanks Member is considered first, because thicknesses, facies, and other geologic relations are somewhat better known than those parameters of the Rainier Mesa Member. The areas of collapse related to eruption of the Ammonia Tanks Member are inferred mainly from sequences more than 300 m (1,000 ft) thick that are strongly devitrified and contain granophyric pumice. Inside Timber Mountain caldera the main area of collapse is outlined in figure 16. Another probable area of Ammonia Tanks collapse is indicated in the Oasis Valley caldera segment by the 450-m-thick (1,500-ft) strongly devitrified Ammonia Tanks exposed on Oasis Mountain. The thick granophyric facies of the Ammonia Tanks Member on Timber Mountain resurgent dome was penetrated in drill hole UE18r (fig. 3), but core from the drill hole lacks the upper part of the Ammonia Tanks, suggesting that the area occupied by Timber Mountain dome further collapsed within an innermost ring-fracture zone, inside the area of outer collapse enclosed by the 300-m isopach (fig. 16). The area around the large mass of pre-Ammonia Tanks rhyolite lava (fig. 16) is obviously outside the caldera related to Ammonia Tanks collapse, although it is inside the prominent north wall of Timber Mountain caldera. Between this north wall and the inferred wall related to Ammonia Tanks collapse (fig. 16), the Ammonia Tanks Member is glassy, partly welded, and less than 60 m (200 ft) thick—typical of the extracaldera facies.

Similar relations occur just inside the south wall of Timber Mountain caldera along a narrow annular zone about 1.5 km wide in which a pre-Ammonia Tanks lava flow is overlain by thin glassy Ammonia Tanks (fig. 16). This narrow zone, obviously, was not within the collapse area related to the Ammonia Tanks Member, but this zone is within the caldera wall continuous with that related to the eruption of the Rainier Mesa Member.

Oasis Mountain (fig. 16) occurs in a large westerly salient or "scallop" of the Oasis Valley caldera segment. The mountain is composed of at least 450 m (1,500 ft) of dense devitrified ash-flow tuff of the Ammonia Tanks having very low porosity. The general attitude of the Ammonia Tanks as determined by the basal contact (fig. 23) and by a prominent parting in the middle is 30°-35° eastward, but in the upper part stretched granophyric pumice dips 70°-80°. The upper part probably slid downdip, possibly as a result of caldera collapse farther east in the caldera segment.

The Ammonia Tanks thins to about 150 m (500 ft) over moderately westward-dipping Rainier Mesa in the Transvaal Hills (fig. 23) on the east edge of the Oasis Valley caldera segment; a 10°-15° angular discordance occurs between the Ammonia Tanks and Rainier Mesa. Locally, an angular unconformity as much as 10° occurs between the westerly dipping upper and lower parts of the Ammonia Tanks. The thinner upper part chilled to a vitrophyre and is locally "frozen" to the thicker more vitrified lower part. The local small angular discordance and the implied partial cooling break indicate minor contemporaneous westward tilting during emplacement of the Ammonia Tanks Member.

In summary, the area of collapse related to the eruption of the Ammonia Tanks was mainly peripheral to the Timber Mountain resurgent dome, because that is where the Ammonia Tanks is thickest and where the resurgence took place. High-silica rhyolite lavas that petrologically resemble parts of the Ammonia Tanks are present in the Timber Mountain caldera moat just outside the area of collapse. Thicknesses of more than 450 m (1,500 ft), steeply dipping stretched pumice at Oasis Mountain, and a local 10° angular unconformity within gently westward dipping Ammonia Tanks in the Transvaal Hills suggest that the floor of the Oasis Valley caldera segment partially subsided and tilted westward with the eruption of the Ammonia Tanks. This subsidence, however, was considerably less than that peripheral to Timber Mountain dome.

The approach to the problem of the area of Rainier Mesa subsidence is more indirect and perhaps less convincing than in the case of the Ammonia Tanks. Several years ago D. C. Noble (written commun., 1966) suggested that the area of collapse related to the eruption of the Rainier Mesa Member included not only Timber Mountain caldera, but also Oasis Valley caldera segment and most of Sleeping Butte segment as well. There was little direct evidence to support his hypothesis at the time, but as geologic mapping and field checking became completed in the caldera segments west of Timber Mountain caldera, the hypothesis of a larger area of subsidence related to the Rainier Mesa eruption has become more attractive.

There can be little doubt that the topographically defined Timber Mountain caldera was the main site of collapse caused by eruption of the Rainier Mesa Member. Under the description of debris flows, emphasis was placed on the unique intertonguing relation of the debris with the uppermost part of the Rainier Mesa Member, and on the fact that the debris flows lap onto the north and east walls of the topographically defined Timber Mountain caldera. The debris flows, moreover, contain blocks locally derived from the adjacent caldera wall. Clearly then, the debris flows, at least the basal parts of them that intertongue with the uppermost Rainier Mesa, record the late stages of collapse related to the eruption of the Rainier Mesa (Byers and others, 1968). The onlapping relation of the debris flows to the caldera wall outlines the limits of structural movement related to extrusion of the Rainier Mesa. Although the Rainier Mesa and the debris flows are buried by younger deposits elsewhere around the continuation of the caldera wall, the continuation of the wall and onlapping thin Ammonia Tanks at a few places just inside the wall indicate that Timber Mountain caldera, as defined herein, was also the site of collapse associated with eruption of the Rainier Mesa Member as well as the Ammonia Tanks.

The Transvaal Hills (fig. 14) form the exposed west wall of Timber Mountain caldera as topographically defined—yet here the Rainier Mesa Member is more than 450 m (1,500 ft) thick, and the base is not exposed. The unit has a gray granophyric texture, typical of thick ash-flow tuffs. Debris flows intertongue with the uppermost Rainier Mesa and overlie it in the same relation as within Timber Mountain caldera. Although the Rainier Mesa dips about 25° W., suggesting a dip outward away from the caldera wall, the debris flows exposed between the Rainier Mesa and the Ammonia Tanks thin and pinch out northward in the Transvaal Hills along a line about 5 km (3 mi) north of the south wall of the Oasis Valley caldera segment. Moreover, the debris flows are exposed under the Ammonia Tanks for a few miles westward just inside the south wall of Oasis Valley caldera segment, analogous to the relations along the north and east walls of Timber Mountain caldera.

At Oasis Mountain (figs. 14, 16), in the westerly salient or "scallop" of the Oasis Valley caldera segment, the thick eastward-dipping Ammonia Tanks rests on at least 90 m (300 ft) of debris flows, whose base is not exposed (see fig

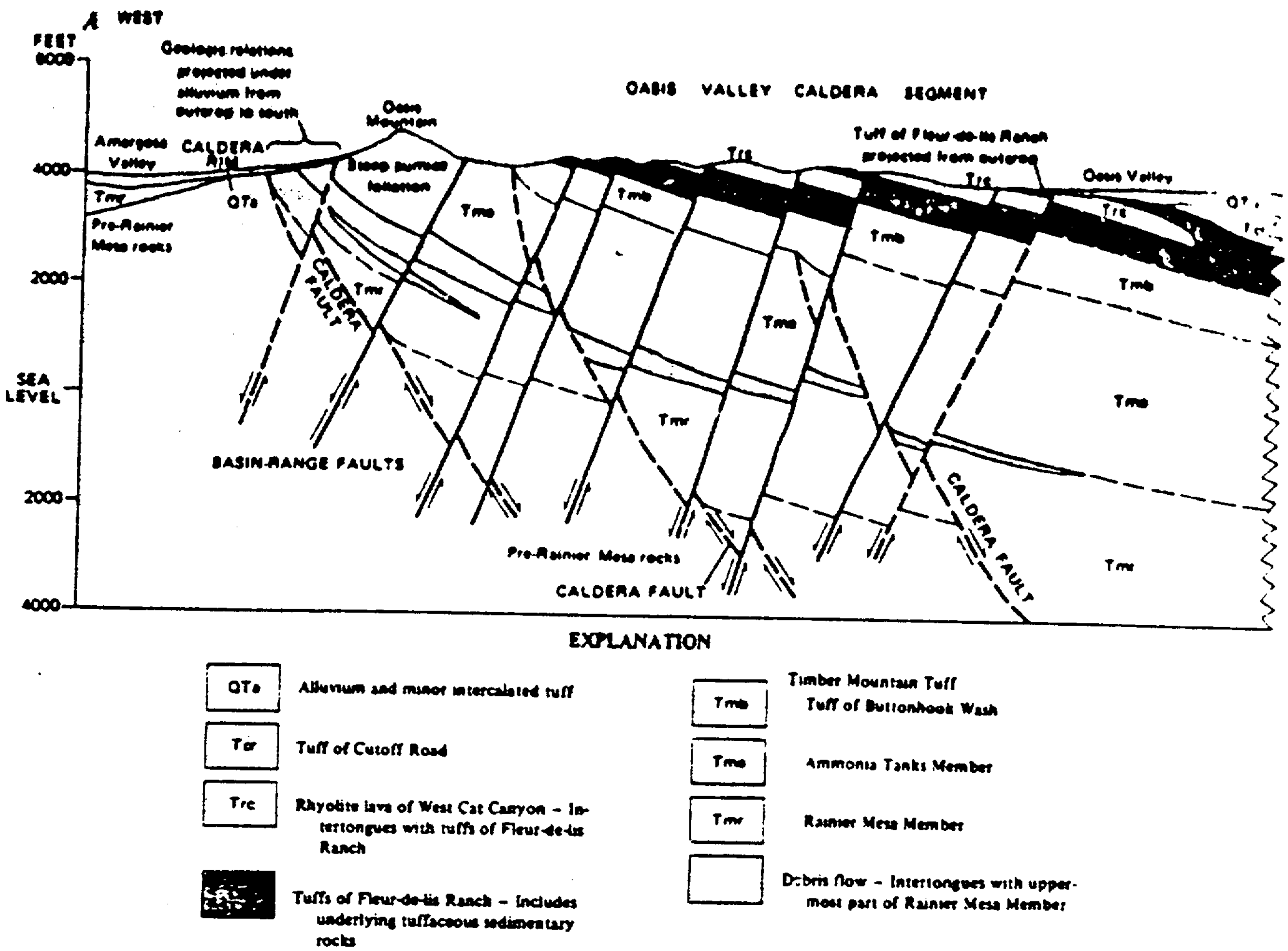
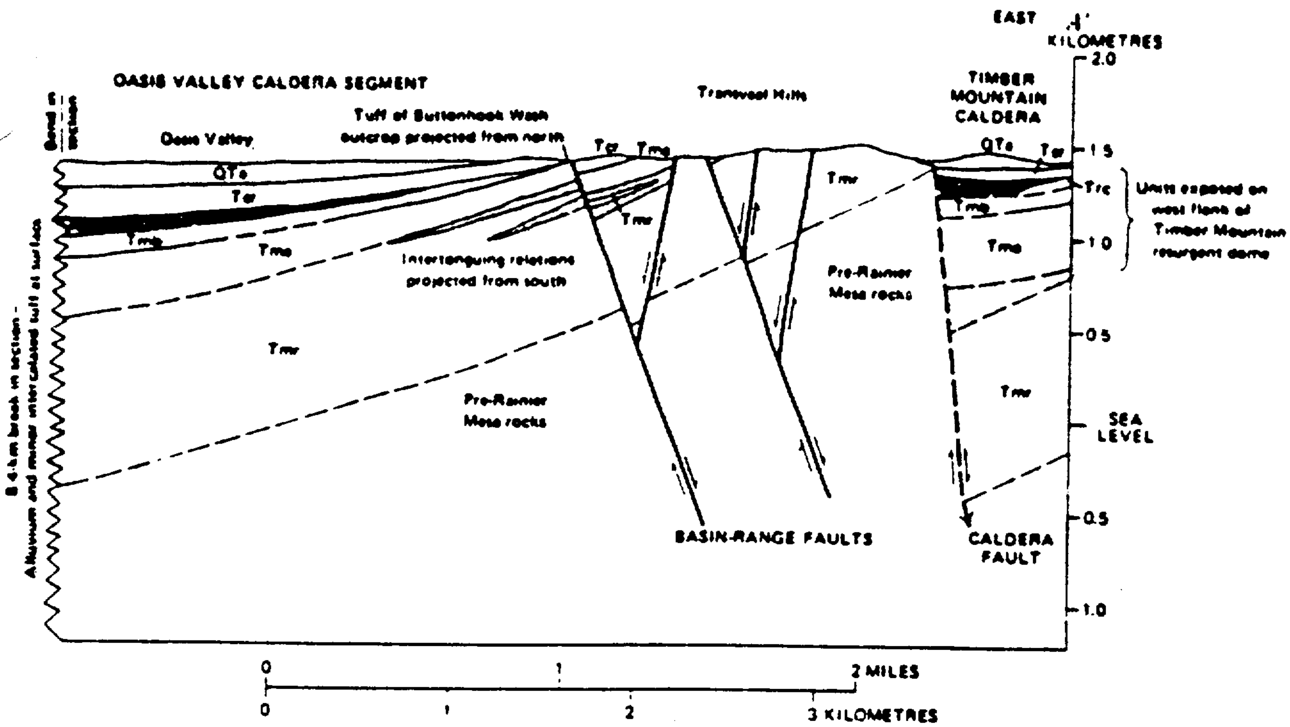


FIGURE 23 (above and right).—Geologic section across Oasis Valley caldera segment, showing great thickness of Rainier Mesa and Ammonia Tanks Members and presence of debris flows of Timber Mountain caldera on east and west sides of segment. Line of section shown in figures 14 and 16. Geology of Oasis Valley area from P. P. Orkild, K. A. Sargent, and R. L. Christiansen (unpub. data, 1971).

23). The debris flows contain rhyolite blocks of the Rainier Mesa and Tiva Canyon Members similar in lithology to the same units exposed in the Bullfrog Hills to the west. Again, these relations are analogous to those inside Timber Mountain caldera, where blocks in the debris flows are derived from the adjacent wall. In fugure 23, we have interpreted the western limit of Rainier Mesa collapse to lie just west of Oasis Mountain. The deeper part of the cauldron subsidence was probably a few miles farther east under Oasis Valley, as indicated by a strong gravity gradient (D. L. Healey, written commun., 1969).

Alternatively, the thick exposure of the Rainier Mesa sheet in the Transvaal Hills may not have accumulated in its own cauldron subsidence, but may have accumulated in an earlier Oasis Valley segment of the Claim Canyon cauldron, as suggested by Christiansen and others (1976). We recognize this probability, because the outline of the buried Claim Canyon cauldron shown in figures 8 and 10 includes the Transvaal Hills. However, the additional evidence, just cited, concerning the extent of the debris flows around the edges of Oasis Valley caldera segment suggests partial collapse during the Rainier Mesa eruptions.

Also suggesting that the west wall of the subsidence associated with the Rainier Mesa eruption may be west of the Transvaal Hills are the two, Rainier Mesa-related, high-silica rhyolite lavas just east and north of Beatty (fig. 14). Other lavas previously discussed, especially the pre-Ammonia Tanks lavas (fig. 16), are generally within a few kilometres of the cauldron subsidence associated with the petrologically related tuffs. The high-silica rhyolite petrologically related to the Rainier Mesa Member (fig. 15) in the Bullfrog Hills (fig. 14) would be more than 15 km (9 mi) away from a caldera wall located in the Transvaal



Hills. It is far more likely, on the basis of comparison of the location of other rhyolite lavas to known related cauldron subsidences, that the Oasis Valley caldera segment collapsed during eruption of the Rainier Mesa. The availability nearby of high-silica rhyolite magma indicates that the volatile-rich magma near the top of magma chamber probably underlay Oasis Valley.

D. C. Noble (written commun., 1966) interpreted the westward-dipping thick Rainier Mesa Member in the Transvaal Hills to be the tilted remnant of a central resurgent dome. According to the resurgent dome hypothesis, post-Rainier Mesa magmatic pressure related to an underlying mobile body of batholithic proportions may have caused the uplift and westward tilt, possibly forming a central resurgent dome that foundered with the eruption of the Ammonia Tanks Member. Christiansen and others (1976), however, emphasize several observations that are detrimental to the hypothesis.

In conclusion, we believe the evidence strongly suggests that westward tilting and partial subsidence of the Oasis Valley caldera segment may have occurred along with subsidence of the Timber Mountain caldera during eruptions of both the Rainier Mesa and Ammonia Tanks Members. These repeated composite subsidences would thereby outline a volcano-tectonic depression, as originally defined by van Bemmelen (1950, 1939). The Timber Mountain caldera and its adjoining Oasis Valley caldera segment probably overlay the apical part of a magma chamber of batholithic magnitude.

YOUNGER INTRACALDERA ROCKS IN TIMBER MOUNTAIN AND OASIS VALLEY CALDERAS

Following the climactic eruptions and resurgence at the Timber Mountain center there was a brief period of relative quiescence with local small lakes in the caldera moat. The earliest bedded tuffs on the flank of the dome are sandy, well sorted, and cross-laminated. These features suggest that the ash-fall tuff was reworked by water and that little, if any, volcanic activity took place. Moreover, the earliest mafic lavas are palagonitized, which suggests interaction with water. Locally as much as 30 m (100 ft) of sediments accumulated, including calcareous sandstone and siltstone in both Oasis Valley and Timber Mountain calderas. Upon renewal of volcanic activity, the composition of the first intracaldera tuffs and lavas had drastically changed from highly silicic rhyolites of the Timber Mountain Tuff, to plagioclase-rich low-silica rhyolites, rhyodacite, and mafic lavas. The chemical character, however, of the post-Timber Mountain rocks remained alkali-calcic.

RHYODACITIC AND MAFIC LAVAS

The oldest post-Timber Mountain rocks to be extruded on the flank of the resurgent dome were intermediate to mafic lavas and relatively restricted in volume. Two of the largest areas of these lavas are on the east and south flanks of Timber Mountain dome (fig. 24). The smaller lava flow on the southern flank is an olivine-bearing trachyandesite (latite of Lipman, Quinlivan, and others, 1966) which has

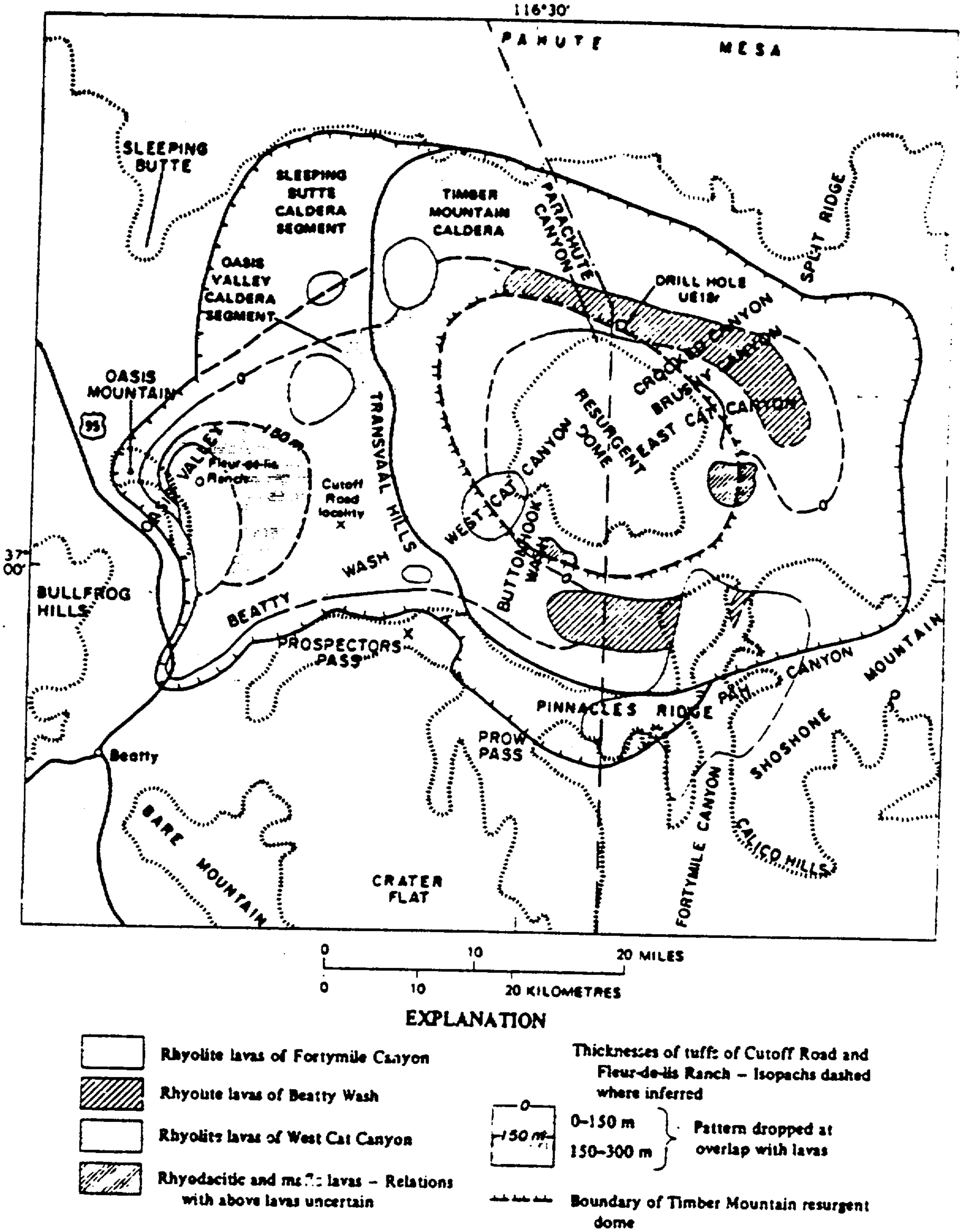


FIGURE 24.—Distribution of younger intracaldera rocks of Timber Mountain-Oasis Valley caldera complex. Rhyolite lavas of Beatty Wash in northern moat are inferred from drill-hole data and negative aeromagnetic anomaly.

10-percent phenocrysts consisting of 90-percent plagioclase and 10-percent olivine, biotite, clinopyroxene, and orthopyroxene. The larger lava flow on the east flank is more exposed and has been more extensively sampled than the smaller flow. The larger lava flow is a phenocryst-rich rhyodacite whose mode and silica content are shown graphically in figure 25. A complete chemical analysis of this rock was furnished by W. D. Quinlivan and P. W. Lipman (written commun., 1974).

TUFFS OF FLEUR-DE-LIS RANCH AND RELATED RHYOLITE LAVAS

The tuffs of Fleur-de-lis Ranch are most completely exposed on the west side of Oasis Valley just west of the Fleur-de-lis Ranch (fig. 24) where three petrographically similar ash-flow tuff cooling units include an intercalated lava flow between tuff units 2 and 3. Tuff units 1 and 2 crop out only at this locality where the aggregate thickness of all three tuffs and the lava is about 300 m (1,000 ft). Tuff unit 3 and the underlying lava extend southward: Oasis Valley is a narrow gorge where it cuts through these units. The only other place where a similar tuff is exposed is beneath a lava plug dome in an old vent south of Beatty Wash (fig. 24). Here a partly fused tuff, possibly a vent-related hot ashfall, dips inward toward the center of the plug dome and encloses it.

The lavas at both localities are modally closely similar to the enclosing tuffs of Fleur-de-lis Ranch and also to the rhyolite lava at West Cat Canyon (figs. 24, 25), where the tuffs are absent. For convenience, all these lavas are designated the rhyolite lavas of West Cat Canyon.

The tuffs of Fleur-de-lis Ranch and the related rhyolite lavas of West Cat Canyon rest on the oldest bedded tuff and sediments that fill Oasis Valley and Timber Mountain calderas and are overlain by the tuff of Cutoff Road, which is included with the tuffs of Fleur-de-lis Ranch in figure 24. Both the tuffs and the associated lavas are probably thicker and more extensive at depth under the Oasis Valley caldera segment. The tuffs have not been found flanking Timber Mountain dome, but the presence of the modally similar rhyolite lava at West Cat Canyon on the southwest flank of the dome (fig. 24) suggests the possibility of a concealed onlap (Byers and others, 1976, sec. *B–B'*).

The similar modes of the tuffs and lavas are shown graphically in figure 25. Individual specimens vary somewhat with respect to total phenocrysts, but the most common phenocrysts are plagioclase, biotite, and clinopyroxene—very similar to those of the dominant mafic pumice in the quartz latitic caprocks of the Paintbrush and Timber Mountain Tuffs. One specimen from the intercalated lava west of Fleur-de-lis Ranch north of Oasis Valley gorge contains hornblende and clinopyroxene; specimens collected south of the gorge contain only clinopyroxene. Possibly two separate lava flows at the same stratigraphic position were sampled. Chemical analyses of the uppermost tuff at Fleur-de-lis Ranch and the rhyolite lava at West Cat Canyon are from W. D. Quinlivan and P. W. Lipman (written commun., 1974). The high alkalis and silica and high normative quartz and alkali feldspars with low normative anorthite indicate rhyolitic compositions, in contrast to more quartz latitic compositions of crystal-rich caprocks of Paintbrush and Timber Mountain Tuffs. The magnetic polarity of the upper tuff is normal (G. D. Bath, oral commun., 1964).

TUFF OF CUTOFF ROAD AND RELATED RHYOLITE LAVAS

The tuff of Cutoff Road and the rhyolite lavas of Beatty Wash, which are compositionally equivalent, are the youngest ash-flow tuff and related lava confined to the Timber Mountain and Oasis Valley calderas. The tuff occurs in the Timber Mountain caldera moat area and around the exposed edges of the Oasis Valley caldera segment (fig. 24). The rhyolite lavas of Beatty Wash are exposed in Beatty Wash in the southern part of Timber Mountain caldera moat (fig. 24) and extend eastward under younger rhyolite lavas of Fortymile Canyon. A lava flow of the same modal petrography crops out in the bottom of Fortymile Canyon (fig. 24) beneath the rhyolite lavas of Fortymile Canyon but is included with these overlying rhyolite lavas on the geologic map of the Timber Mountain caldera area (Byers and others, 1976). Another lava flow, about 150 m (500 ft) thick, was penetrated in drill hole UE18r in the northern caldera moat; its inferred extent is based partly on a negative aeromagnetic anomaly (G. D. Bath, written commun., 1968) and partly on structural interpretation of the moat area.

The tuff of Cutoff Road does not exceed 60 m (200 ft) in thickness where exposed; commonly it is less than 30 m (100 ft) and nonwelded, except in Oasis Valley on the west side of the Oasis Valley caldera segment. Near the distal nonwelded edge on the east flank of Timber Mountain dome, a maximum thickness of 26 m (85 ft) is exposed where the tuff dips gently eastward under cover. The rhyolite lavas of Beatty Wash are 150 m (500 ft) thick in the northern moat and greater than 60 m (200 ft) thick in the southern moat. The lavas are probably a significant fraction of the total, owing to the greatly reduced volume of tuff erupted from post-Timber Mountain Tuff vents of the Timber Mountain–Oasis Valley caldera complex.

The tuff of Cutoff Road locally onlaps the rhyolite lava of Beatty Wash in Beatty Wash, but there is less than 3 m (10 ft) of coarse locally derived ash-fall tuff between the units. The tuff overlies the tuffs of Fleur-de-lis Ranch or its associated lavas, but the rhyolite lava of Beatty Wash has

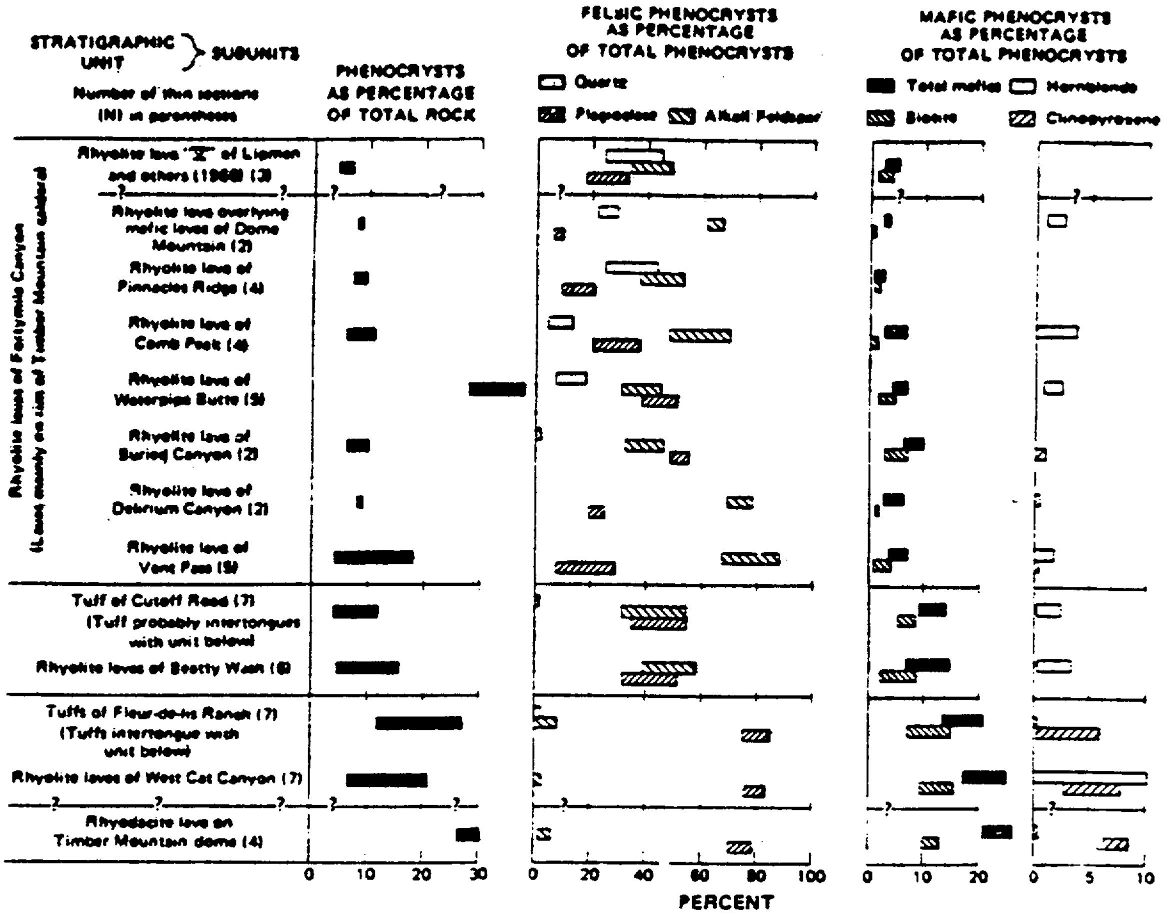


FIGURE 25.—Modal and silica ranges of younger, intracaldera volcanic rocks of Timber Mountain-Oasis Valley caldera complex, uncertain field relation. Rhyolite lava "V" (Lipman, Quinlivan, and others, 1966) may correlate with rhyolite of Pinnacles cryst is absent. Silica analyses from W. D. Quinlivan and P. W. Lipman (written commun., 1974).

not been observed in direct stratigraphic contact with these units. The tuff of Cutoff Road and the rhyolite of Beatty Wash are inferred to be slightly younger than the tuffs of Fleur-de-lis Ranch and the rhyolite lavas of West Cat Canyon, as indicated partly by superposition of the tuff units and partly by inferred near-equivalence in time of petrographically similar tuff and rhyolite lava.

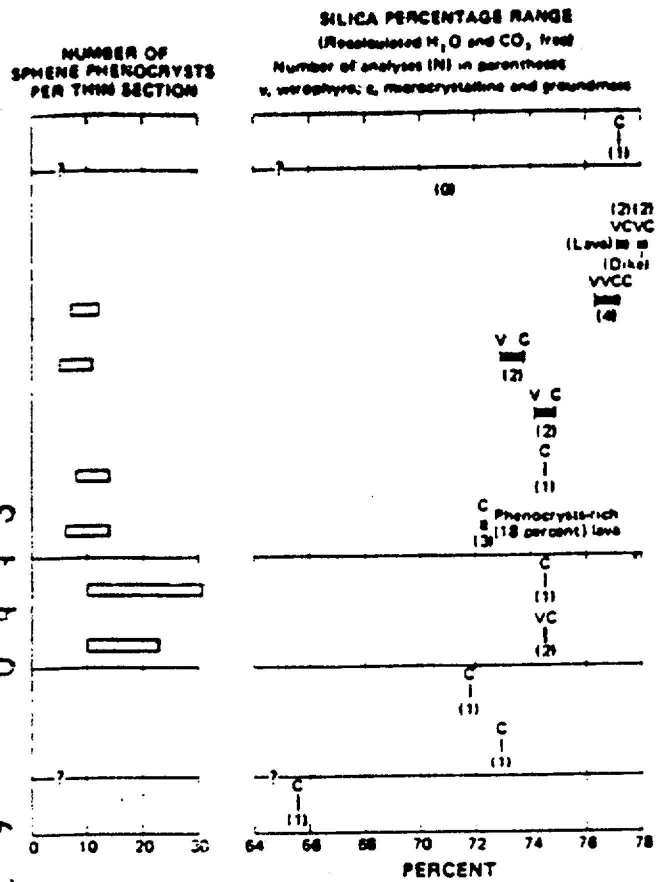
The thin-section modes of the tuff of Cutoff Road and of the rhyolite lavas of Beatty Wash are nearly identical, even in the relative abundance of sphene (fig. 25). The only slight difference is the presence of sparse quartz in a few of the tuff thin sections. Both rocks are rhyolites having identical silica content at 74.5 percent (fig. 25) and therefore can be correlated as one stratigraphic unit.

A mean K-Ar age on the tuff of Cutoff Road is 9.5 m.y. as reported by Kistler (1968, table 1, "tuff of the caldera fill"). The magnetic polarity for both the tuff and the rhyolite of Beatty Wash is reversed from the Earth's present field (G. D. Bath, written commun., 1968).

RHYOLITE LAVAS OF FORTYMILE CANYON

The last activity of the Timber Mountain center resulted in a sequence of rhyolitic lava flows, domes, and closely associated air-fall pyroclastic rocks erupted from a zone along and just outside the south and west rims of the Timber Mountain caldera. The lavas flowed mainly southward across the outer flank of the caldera structure but also flowed into the caldera moat, and at one place lapped onto the Timber Mountain resurgent dome (fig. 24). These rocks have been designated collectively the rhyolite lavas of Fortymile Canyon (Christiansen and Lipman, 1965; Orkild and O'Connor, 1970).

The rhyolite lavas of Fortymile Canyon include eight known individual lava flows and domes (fig. 25), each associated with a sequence of pyroclastic rocks, mainly bedded tuffs. These flow units and their tuffs have been mapped individually on the 7½-minute quadrangle maps (fig. 2; Christiansen and Lipman, 1965; Orkild and O'Connor, 1970). No stratigraphic thickness is meaningful for the unit as a whole because of the limited areal extent and the large variations in thickness of individual flows. Flows are as thick as 300 m (1,000 ft) where they fill old valleys. The pyroclastic rocks in most instances thin outward from the vent areas, where piles of tuff and agglomerate associated with a single flow are as much as



in order of stratigraphic succession, except as noted. Query indicates
Ridge (Christiansen and Lipman, 1965, 1966). Blank indicates pheno-

250 m (800 ft) thick. The rhyolite lavas of Fortymile Canyon contain about 20 km³ (5 mi³) of erupted material.

The content of silica nad quartz phenocrysts in the rhyolite lavas of Fortymile Canyon increases upward from quartz-poor flows at the base to quartz-rich flows at the top (fig. 25). The quartz trend seems to repeat a similar trend in the Paintbrush-Timber Mountain Tuff sequence. The silica content of the lavas increases gradually upward to high-silica rhyolite (fig. 25), also similar to the trend in the tuffs and rhyolites of Area 20 that fill the Silent Canyon caldera. The petrochemical trend of these lavas toward high quartz and silica continues the trend of the older postresurgence lavas and tuffs in the caldera moat. Rhyolite "V" of Lipman, Quinlivan, Carr, and Anderson (1966) is a high-silica rhyolite (figs. 24, 25) with thin-section modes almost identical to those of the rhyolite lava of Pinnacles Ridge (fig. 25), suggesting either approximate contemporaneity or the tapping of high-silica rhyolite magma near the top of the magma chamber at different times.

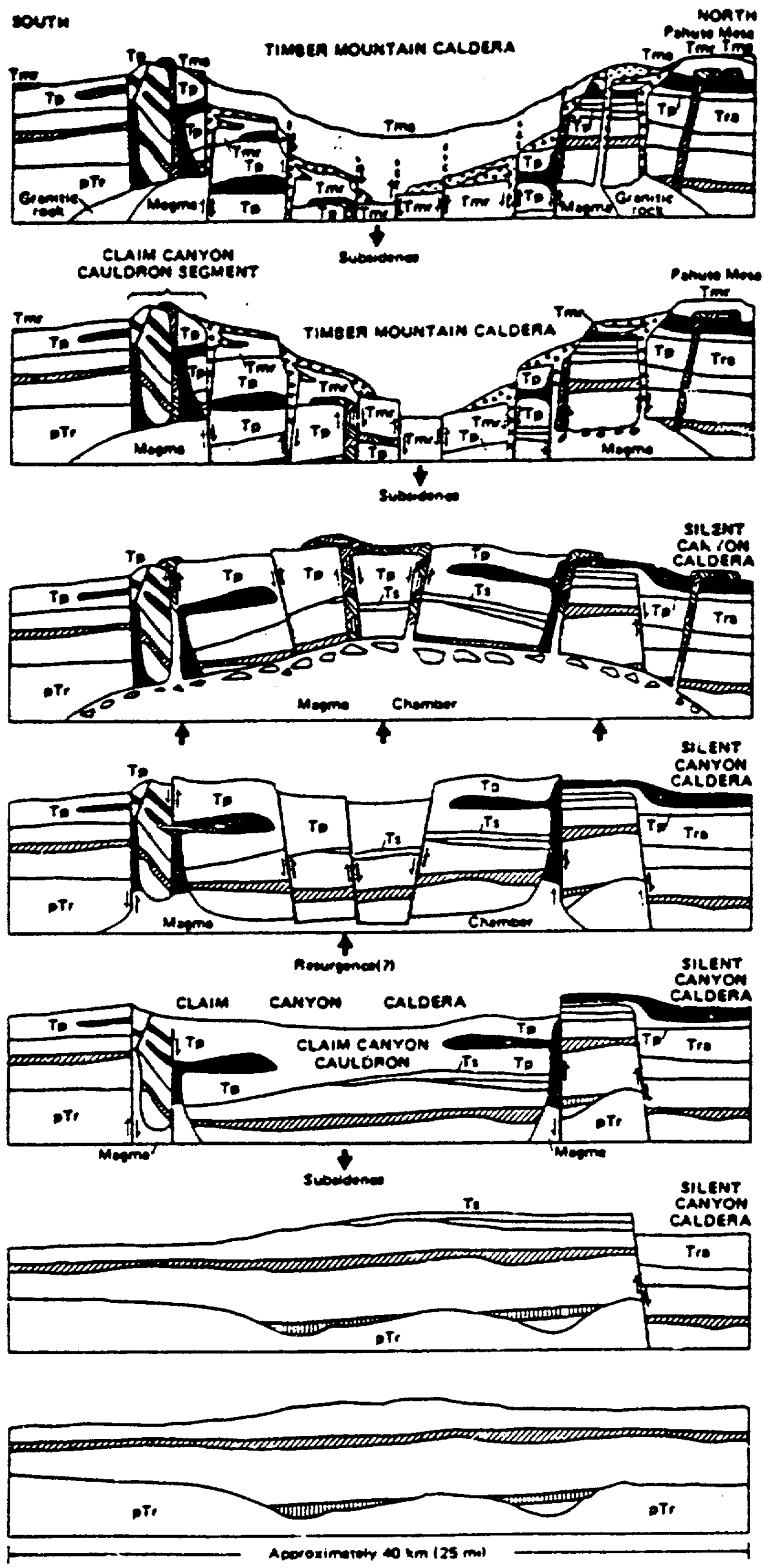
The rhyolite lavas of Fortymile Canyon are petrochemically and structurally related to volcanism of the Timber Mountain center and are probably the last eruptive products of that episode. Their age is bracketed by a K-Ar age date of 9.5 m.y. on the underlying tuff of Cutoff Road and by a K-Ar date of 7.5 m.y. on the overlying Thirsty Canyon Tuff (Kistler, 1968) from the Black Mountain caldera center. The petrochemical trend of the rhyolite lavas both repeats the main eruptive sequence of the Timber Mountain-Oasis Valley caldera complex and continues the trend of the younger intracaldera rocks, thereby concluding the activity related to the Timber Mountain center about 9 m.y. ago.

SUMMARY OF GEOLOGIC HISTORY

Prior to about 16 m.y. ago the area of the Timber Mountain–Oasis Valley caldera complex was probably a terrane of basin-range-type block-faulted mountains of relatively low relief, separated by valleys partially filled with alluvium and tuff. The vents from which the tuff was erupted were outside the area. The youngest of these old tuffs, the calc-alkalic Fraction Tuff, is slightly more than 16 m.y. old (all K-Ar dates from Kistler, 1968, or Marvin and others, 1970); it flowed into the ancestral valleys of the Timber Mountain-Oasis Valley area from vents to the north (Ekren and others, 1971).

The earliest known volcanic activity in the Timber Mountain–Oasis Valley caldera complex was the eruption of predominantly hornblende-bearing calc-alkalic ash-flow and bedded tuffs and subordinate rhyolite lavas, probably related to the Sleeping Butte caldera whose northwest wall is exposed in northern Oasis Valley. Little is known of the extent of this early caldera, and for that reason only the extracaldera extrusive products are shown in diagram 1 of figure 26. The principal extrusives from the Sleeping Butte caldera include the Redrock Valley and Crater Flat Tuffs. These ash flows possibly constituted as much as 1400 km³ (350 mi³) of tuff deposited around and within the Timber Mountain–Oasis Valley caldera complex. The Bullfrog Member of the Crater Flat Tuff is the most extensive, possibly extending into Death Valley to the west. The extracaldera extent of the overlying Prow Pass Member is on the south side of the complex. The Prow Pass Member is the only known tuff with orthopyroxene as the chief mafic phenocryst. These eruptive events took place 16 to 14 million years ago.

A major collapse within the Silent Canyon caldera (diagram 2, fig. 26) occurred 13.8 m.y. ago with the eruption of the peralkaline Grouse Canyon Member of the Belted Range Tuff. The Silent Canyon caldera is not part of the Timber Mountain–Oasis Valley caldera complex, from which only calc-alkalic and alkali-calcic rocks are known. Following the early peralkaline eruptions, the Silent Canyon caldera was the source of calc-alkalic rocks, mainly the tuffs and rhyolite lavas of Area 20 inside the caldera and the Stockade Wash Tuff outside the caldera. The Stockade Wash was formerly the lowermost member of the alkali-calcic Paintbrush Tuff but differs litho-



7

Extrusion of pre-Ammonia Tanks lavas followed by eruption of Ammonia Tanks Member and tuff of Buttonhook Wash. Further cauldron subsidence

11.1 m.y.

6

Eruption of Rainier Mesa Member accompanied by multiple collapse and emplacement of debris from caldera wall onto floor of caldera and into ring fissures

11.3 m.y.

5

Broad doming accompanied by extrusion of pre-Rainier Mesa lavas

11.3-12 m.y.

4

Possible resurgence of Claim Canyon cauldron at early stage of magmatic doming

12-12.5 m.y.

3

Eruption of Paintbrush Tuff and related lavas with recurrent subsidence within Claim Canyon cauldron

12.5-13 m.y.

2

Eruption of Grouse Canyon Member and major collapse within Silent Canyon caldera followed by eruption of tuffs and rhyolites of Area 20 inside caldera and by eruption of Stockade Wash Tuff outside caldera. Episodic cauldron subsidence

13-14 m.y.

1

Eruption of pre-Grouse Canyon tuffs and lavas on eroded pre-Tertiary rocks. Probable subsidence at Sleeping Butte caldera west of line of section

14-16 m.y.

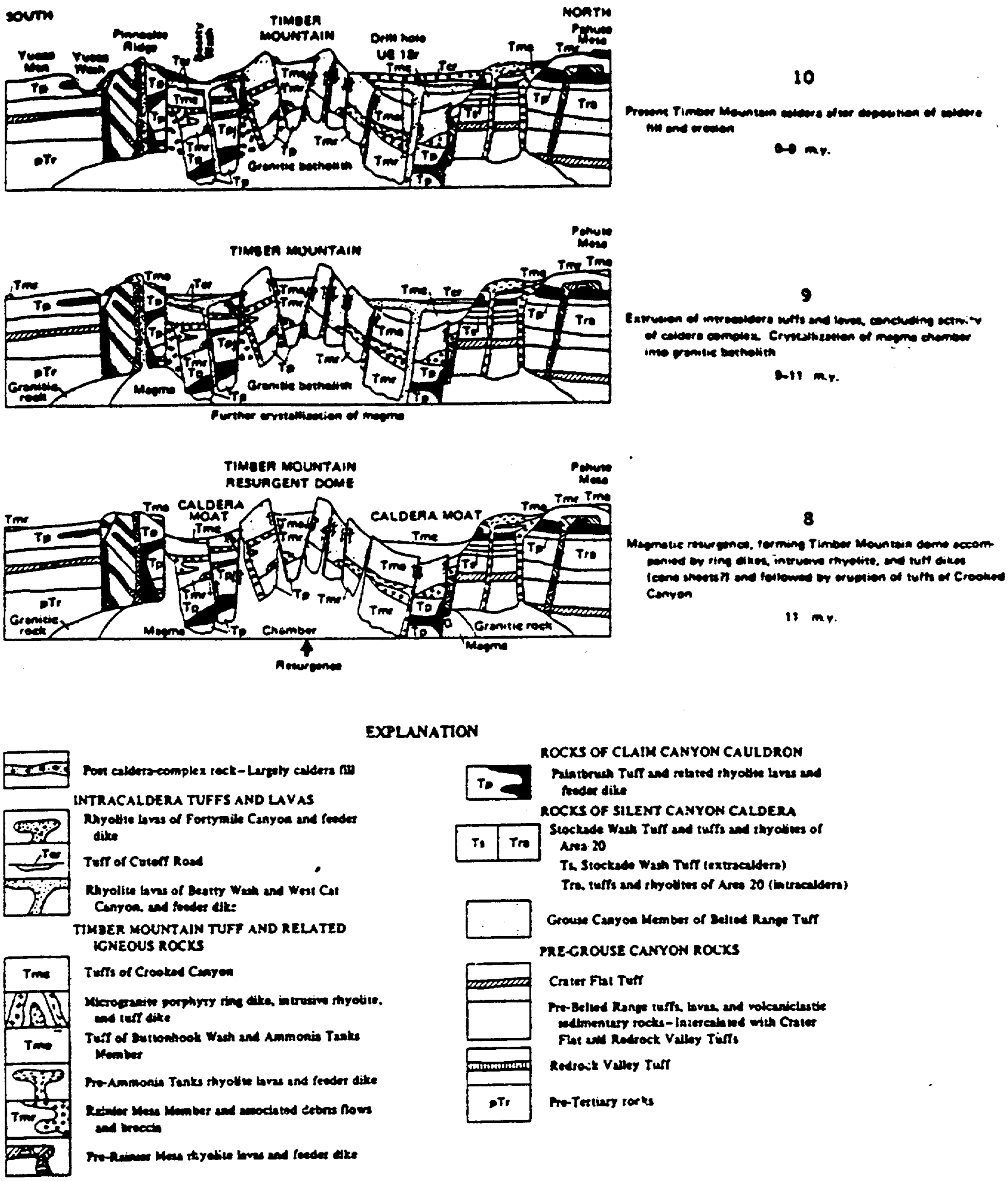


FIGURE 26 (left and above).—Sequence of interpretive diagrams through Timber Mountain caldera, illustrating volcanic history of the Timber Mountain-Oasis Valley caldera complex.

logically and petrographically from members of the Paintbrush Tuff, as now defined, and is more closely related in its petrography to the intracaldera tuffs and rhyolites of Area 20. The xenolithic inclusions of intracaldera Grouse Canyon and the areal distribution of the Stockade Wash indicate a source within the Silent Canyon caldera. The total erupted volume of the Stockade Wash was about 20–40 km^3 (5–10 mi^3). Recurrent minor subsidences probably occurred within Silent Canyon caldera as the thick sequence of tuffs and rhyolites of Area 20 accumulated inside the caldera, with the result that the underlying Crater Flat Tuff was eventually downdropped more than 2 km (diagram 2, fig. 26).

The members of the Paintbrush Tuff and petrologically related alkali-calcic lavas were erupted from the Claim Canyon cauldron (diagram 3, fig. 26) resulting in a caldera of unknown extent. Only a small segment of the Claim Canyon cauldron is now exposed, but the general size and location of the collapse structure can be inferred, from distribution of tuffs and lavas north and south of Timber Mountain caldera, to be about 25 km (15 mi) in diameter and to be centered several kilometres west of the present summit of Timber Mountain. The oldest member of the Paintbrush Tuff, the Topopah Spring, was erupted about 13 m.y. ago with a total volume of about 250 km^3 (60 mi^3). Recurrent subsidence within the cauldron followed eruption of the Topopah Spring Member of the Paintbrush Tuff, and probably a minor collapse followed the eruption of the Pah Canyon and Yucca Mountain Members. Within the caldera they accumulated to several times their thickness outside the caldera. The Tiva Canyon Member, representing the climactic eruption in the evolution of the Claim Canyon cauldron, flowed out about 12.5 m.y. ago mainly to the west of the Claim Canyon cauldron. The tuff of Chocolate Mountain, which is about 1,000 m (3,300 ft) thick, was erupted as a late quartz latitic phase of the Tiva Canyon and was confined within the Claim Canyon cauldron, suggesting that collapse was occurring during its eruption, although Christiansen and others (1976) infer a collapse to the west of the site of Oasis Valley. Tuff breccia, similar petrographically to the Tiva Canyon, was generated at vents along or near the wall of the Claim Canyon cauldron segment. The volume of the Tiva Canyon, including the intracauldron tuff of Chocolate Mountain, may have totaled as much as 1,000 km^3 (250 mi^3). The youngest separate cooling unit of the Paintbrush, the tuff of Pinyon Pass, followed very soon after the Tiva Canyon was confined to the newly formed caldera.

After eruption of the ash-flow sheets of the Paintbrush Tuff and after the formation of the caldera, intricate faulting occurred within the Paintbrush cauldron, similar to that on Timber Mountain. The fault pattern is interpreted by the present authors (see also Christiansen and others, 1976) as owing to magmatic resurgence with uplift of the cauldron block from its former subsided position (diagram 4, fig. 26). The entire Paintbrush cauldron later participated in a broad magmatic doming preliminary to the culminating stages of volcanism—the eruption of ash-flow sheets of the Timber Mountain Tuff. Quartz-bearing pre-Rainier Mesa rhyolite lavas were extruded from fractures probably related to this broad doming (diagram 5, fig. 26). Gas-charged silicic rhyolitic magma accumulated at the top of the domical chamber, and tuffs were assimilated from the roof as crystallization proceeded lower in the chamber.

The Timber Mountain Tuff chapter of the caldera complex began 11.3 m.y. ago with eruption of the voluminous Rainier Mesa Member from the central part of the broad dome that had formed over the magma chamber. The domed roof over the magma chamber ruptured sufficiently to cause a considerable reduction of pressure and to trigger vesiculation which greatly increased the volume of the gas-charged magma escaping through fissures. As the eruption proceeded, collapse of the roof occurred, and the Rainier Mesa accumulated to a greater thickness inside the subsidence area than outside (diagram 6, fig. 26). As the caldera deepened with continuing eruption a more crystal-rich, but less gas-charged, quartz latitic magma was tapped, whose eruptions were largely confined within the caldera. Poorly sorted debris flows containing large blocks of welded tuff and lava slid off the newly formed oversteepened caldera walls and intertongued with the upper quartz latitic part of the Rainier Mesa Member. A total volume of about 1,200 km^3 (300 mi^3) of tuff had been extruded by this time, and a large volcano-tectonic depression formed, including the Timber Mountain caldera and probably the adjacent Oasis Valley caldera segment. There is little evidence to indicate whether or not there was central resurgent doming of the Rainier Mesa Member within this depression, except for the westward-tilted block in the Transvaal Hills west of Timber Mountain caldera.

During the brief interval between the eruptions of the Rainier Mesa Member and Ammonia Tanks Members of the Timber Mountain Tuff (11.3–11.1 m.y.), pre-Ammonia Tanks rhyolite lavas were extruded within the caldera that had resulted from the Rainier Mesa eruptions (diagram 7, fig. 26).

The Ammonia Tanks Member of the Timber Mountain Tuff was erupted 11.1 m.y. ago. Nearly half its total volume of 900 km^3 (230 mi^3) probably accumulated within a concomitantly subsiding caldera, as evidenced by the fact that no debris flows or breccias are known to intertongue with the tuff. This episode of cauldron subsidence of Timber Mountain caldera occurred within an area somewhat smaller than the Rainier Mesa collapse area (diagram 7, fig. 26) and was centered farther south, with

·e result that a crescent-shaped northern moat block did participate in the Ammonia Tanks subsidence. The ..monia Tanks eruptions reflect compositional trends ıth time that were more complex than earlier ash-flow ıff eruptions. In the ash flows of the Ammonia Tanks ıat were spread outside the caldera the trends progress pward from quartz latite to rhyolite and back to quartz ·tite. This general sequence outside the Ammonia Tanks ıllapse area was represented within the collapse area by a ıuch greater thickness of complex intertonguing rhyolite ıd quartz latite, suggesting multiple source vents and ›ncomitant eruption and collapse.

Central resurgent doming of the Ammonia Tanks nmediately occurred during the emplacement of the late ıtracaldera units of the Timber Mountain Tuff. The ›ming may even have begun before the final ash-flows of ıe Ammonia Tanks had been extruded. The tuff of uttonhook Wash was erupted very shortly after the mmonia Tanks and was confined within the Timber fountain–Oasis Valley caldera complex. During or just ·fore this eruption about 11 m.y. ago, magmatic ·surgence continued and resulted in slight moderate ›ming of the Ammonia Tanks and intrusions of ring ıkes, rhyolite plugs, tuff dikes, and possibly cone sheets ıto the dome (diagram 8, fig. 26). Doming continued and ıe weakly welded tuffs of Crooked Canyon of the Timber fountain Tuff were erupted into the newly formed ıber Mountain caldera moat at a late stage of the .ing. A northwest-trending apical graben formed at ıe crest of the resurgent dome owing to stretching of the ›med mass.

The culminating chapter in the volcanic history of the imber Mountain–Oasis Valley caldera complex was now ver; subsequent eruptions were small and confined to the ıldera moat (diagram 9, fig. 26). The tuffs of Fleur-de-lis anch and Cutoff Road and related lavas were erupted 11 › 9.5 m.y. ago and were confined within the Timber fountain–Oasis Valley caldera complex. They probably ad source vents to the west of Timber Mountain caldera ı the Oasis Valley caldera segment. Local caldera ›llapses probably occurred within the segment ccompanying these eruptions, accounting for the low ·lief of the segment and the caldera fill that postdates the ıff of Cutoff Road. Finally, the rhyolite lavas of Forty- ıile Canyon accumulated on the rim and in the moat of Timber Mountain caldera and concluded the volcanic ıistory of the complex.

The geologic history subsequent to the last volcanic ·ctivity of the Timber Mountain–Oasis Valley caldera omplex includes the partial filling of the caldera moat ·ith mafic lavas, ash-flow tuffs and lavas from the ıeighboring Black Mountain center, and the deposition of an gravels (diagram 10, fig. 26). The Timber Mountain aldera walls and the resurgent dome were somewhat ıified by erosion.

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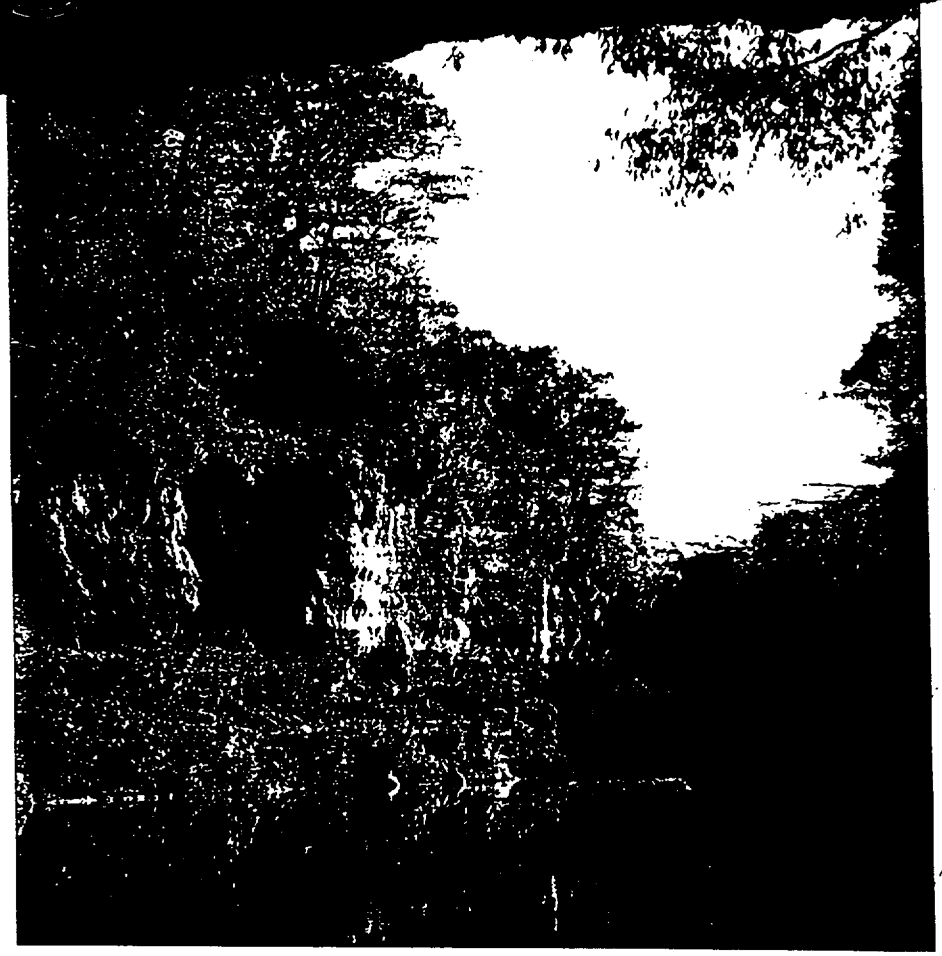
☆U.S. GOVERNMENT PRINTING OFFICE: 1976—677-346/95

Geological Society of America



ABSTRACTS WITH PROGRAMS

1992 Annual Meeting

CINCINNATI

Cincinnati, Ohio • October 26-29

Dr. Albert B. Sabin Cincinnati Convention Center

Associated Societies • Association of Geoscientists for International Development • Association for Women Geoscientists
Cushman Foundation* • Geochemical Society* • Geoscience Information Society* • Mineralogical Society of America*
National Association of Geology Teachers* • National Earth Science Teachers Association • Paleontological Society*
Sigma Gamma Epsilon • Society of Economic Geologists* • Society of Vertebrate Paleontologists
**Representatives serve on the 1992 Joint/Technical Program Committee*

The purpose of this study is to determine which technique provides the most quantitative and easily reproduced data. Image analysis techniques were utilized to produce a digitized, two dimensional maximum area plane of projection of the aggregates. The geometric parameters and Fourier transforms then were calculated from the projections by computer techniques, while printouts of projection planes were used to manually record fractal dimensions. Each technique is limited by the imaging system's magnification ability. Geometric parameters and Fourier analysis are further limited by the fractal nature of the grain perimeter. Recent work indicates that fractal dimensions yield quantitative descriptions, surpassing results of both geometric parameter and Fourier analysis techniques in terms of error and useful application. This illustrates the promising nature of applied fractal dimension studies to the characterization of concrete materials. Funding is being provided by the Florida Department of Transportation.

11:15 a.m. Eckhoff, William R.

DOWNHOLE SHEAR-WAVE VELOCITY STUDIES IN THE UNCONSOLIDATED SEDIMENTS IN EVANSVILLE, INDIANA

ECKHOFF, William R., SAMUELSON, Alan C., Geology Dept., Ball State University, Muncie, IN 47306; EGGERT, Donald L., Indiana Geological Survey, Bloomington, IN 47402

Extensive downhole shear-wave velocity studies of mid-western Quaternary unconsolidated sediments have been undertaken to evaluate seismic hazards in southwestern Indiana. As part of the study, 21 bore holes in Evansville were drilled to obtain data using a 12 channel signal enhanced seismic recorder with a three component downhole geophone. All holes drilled have cuttings and natural gamma ray logs; some holes have split spoon samples and standard penetration test data.

Generally, the data indicates two different depositional environments within the Evansville area. The southern half of the city is underlain by predominantly sand and gravel fluvial deposits that range in thickness from 21 m to 41 m. These sites have an average shear-wave velocity of 244 m/s. The northern and western section of Evansville are underlain by lacustrine deposits with thicknesses of 7 m to 22 m and an average shear-wave velocity of 202 m/s. An east-west trending, mile wide transition zone between these two environments is predominantly sand and gravel with interbedded overbank or lacustrine deposits. This zone ranges from 22 m to 38 m in thickness and has an average shear-wave velocity of 244 m/s.

Shear-wave velocity measurements were made downhole on a 2-5 m interval from surface to hole bottom. Shear-wave velocities are generally slowest in the near surface 2-3 m depth at each site averaging 142 m/s. Not including this shallow zone, the individual sand and gravel downhole measurement intervals have shear-wave velocities averaging 297 m/s and generally increases with depth. The silt and clay overbank and lacustrine intervals have an average shear-wave velocity of 236 m/s.

SESSION 115, 8:00 a.m.

THURSDAY, OCTOBER 29, 1992

GEOMORPHOLOGY (POSTERS)

CCC: Level 1

Booth 1 Coe, Jeffrey A.

PHOTOGRAMMETRIC ANALYSIS OF MODERN HILLSLOPE EROSION AT YUCCA MOUNTAIN, NEVADA

COE, Jeffrey, A., WHITNEY, John, W., US Geological Survey, Denver, CO, 80225; GLANCY, Patrick, A., US Geological Survey, Carson City, NV, 89701

Debris flow processes are a primary mechanism for modern hillslope erosion at Yucca Mountain, Nevada. Modern debris flows are rare events, as is evidenced by the preservation of middle Pleistocene colluvium and the lack of erosional scars on hillslopes. This study characterizes debris flows that occurred on July 21 or 22, 1984, on the south hillslope of Jake Ridge, about 6 km east of the crest of Yucca Mountain. The hillslope gradient ranges from 50 degrees at the top to 3 degrees at the base; the hillslope is underlain by Tertiary ash-flow tuff and is mantled by less than 2 m of varnished bouldery colluvium. Because aerial stereo photographs were available of Jake Ridge from before the 1984 flows, photogrammetric techniques were used to quantify the volume of debris eroded off the slope, as well as to map the redistribution of the eroded sediment.

The Jake Ridge flows were initiated by a convective summer storm. Precipitation gauges 5.4 and 7.5 km southwest of Jake Ridge recorded 64 and 69 mm on July 21, and 22 and 16 mm on July 22, respectively. Measured rainfall rates ranged up to 73 mm/hour on the 21st and 15 mm/hour on the 22nd. Erosion severity at Jake Ridge compared to that near the precipitation gauges implies that greater and more severe rainfall probably occurred at Jake Ridge. Water and debris stripped part of the upper hillslope of colluvium, widened and deepened existing channels, and created new channels on the lower hillslope. Most erosion probably occurred as the combined result of channel scour and soil slips. Debris flowed toward a tributary of Fortymile Wash; a large intermittent stream about 0.6 km from the top of the hill. The photogrammetric study area was 48390 m² and included the entire hillslope. Digital elevation models (DEMs) with 2 m spatial resolution, measured from pre-flow and post-flow aerial stereo photographs using an analytical stereo plotter, were used to estimate the volume and distribution of debris affected by the flow. Volumes were calculated by subtracting the pre-flow elevation from the post-flow elevation at each DEM grid node, multiplying the elevation difference by the area of each node, and summing the cubes. Volumetric calculations show that about 3650 m³ of colluvium were eroded from the hillslope. Maximum depth of erosion was about 1.2 m. Of the 3650 m³ eroded, about 10 % was deposited on the slope as levees and small lobes, 35 % was deposited near the base of the slope, 40 % was deposited in the tributary to Fortymile Wash, and less than 15 % entered Fortymile Wash. These results suggest a model for hillslope erosion during dry interpluvial climates: large, but infrequent storms cause localized hillslope stripping that results in tributary/channel aggradation.

Booth 2 Gillespie, Marcus

THE NATURE OF CHANNEL PLANFORM CHANGE: BRAZOS RIVER, TEXAS

GILLESPIE, Marcus, and GIARDINO, John R., Geography Dept., Texas A&M University, College Station, TX 77843-3147.

Although meandering rivers have been studied extensively, most research has focused on freely meandering rivers in homogenous alluvial environments. Because these types of rivers constitute a small percentage of all rivers, research is needed to assess the nature of planform change on rivers flowing in more complex alluvial environments.

This study describes the nature of planform change that has occurred in three contiguous alluvial reaches of the Brazos River, Texas, from the 1930s to 1988. The reaches encompassed 260 km and more than 125 bends, and were selected based on confluences with two tributaries. Maps of the channel were produced by digitizing the channel centerline from aerial photographs and rectifying the images on a GIS. The nature of bend planform change was described in terms of 14 morphological variables representing bend shape, and other variables characterizing the fluvial environment. A migratory activity index (MAI) was developed which provides an objective means of assessing changes in channel stability.

The MAI indicated that the river's rate of migration has decreased substantially since 1939. This change in behavior results from diminished discharges and sediment loads brought about by flow regulation and is consistent with previous findings on the effects of flow regulation on channel activity. However, the other results were contrary to those found in studies of freely migrating rivers. Bend planform size was controlled not by discharge, but by the presence or absence of resistant rock and sediment layers interspersed among the alluvial sediments in a small number of bends. Although planform controls on migration rates were found, the interaction of variables resulted in poor correlations with migration. Of greatest significance was that 37% of the bends on the river experienced negative migration, i.e., migration toward the baseline connecting the inflection points which define a bend. This phenomenon, which is not a form of meander cutoff, has not been described before and its significance lies in the fact that it precludes the development of predictive models of migration and planform evolution. This is because its occurrence makes it impossible to predict the direction of channel migration. Also of significance is the fact that its occurrence contradicts standard theoretical models of fluid flow and erosion in channel bends which have been developed to describe conditions in freely migrating rivers. Given that most rivers are not freely migrating, the above results pose limitations to the applicability of models based on studies of freely migrating rivers.

Booth 3 Pederson, Darryll T.

MODEL FOR SAND HILLS DEVELOPMENT: GEOMETRY, SEDIMENT SUPPLY AND DEPOSITION, RIVER SYSTEMS AND CLIMATIC IMPLICATIONS

PEDERSON, Darryll T., WAYNE, William J., Geol. Dept. UNL, Lincoln, NE, 68588, and DAVIS, Ralph K. Dept. of Earth Sci., USD, Vermillion, SD 57069

A model of sand hills development was formulated using processes occurring along the Dismal, Middle Loup and Platte rivers. A widespread alluvial fan blanketed by loess and sand dunes with interspersed lacustrine deposits is the product. The great arc of the sediment-supplying river indicates direction of wind transport.

The key is a Platte-like river with flows near threshold capacity for transport of sediment from the river's source through the area during wetter climatic periods. During dryer periods stream channels fill with sediment pulses transported from mountain headwaters during snowmelt flood flows. The flood flows cause vertical reworking and sorting of the sediment. With waning flood flows many stream channels dry up leaving sediments vulnerable to wind erosion and transport. With time stream channels become blocked by aggradation of sediment and dune formation diverting snowmelt floods to new paths in the forming dune field or around the margin of the new dune field. This process continues until increased flows with wetter climates are once again able to transport sediment through the area and erode a new river valley. Rivers rising in sand hills are groundwater fed, uniform in flow, and change only in response to climatic changes. They do not have the energy to rework the extensive gravel deposits of the Platte-like rivers and their net effect is to rework sediment above the coarser alluvium and transport the finer sediment out of the sand hills.

ABSTRACTS WITH PROGRAMS, VOL. 24, NO. 7, 1992 ANNUAL MEETING. ISSN 0016-7592

Use of packrat middens to determine rates of cliff retreat in the eastern Grand Canyon, Arizona

Kenneth L. Cole
Laboratory of Paleoenvironmental Studies, Department of Geosciences, University of Arizona, Tucson, Arizona 85721

Larry Mayer*
U.S. Geological Survey, Menlo Park, California 94025

ABSTRACT

Packrat midden data can be used to calculate rates of cliff retreat by relating midden age to the distance between cliff face and midden. Regression analysis using 14 radiocarbon-dated packrat deposits from the Mississippian Redwall Limestone in the eastern Grand Canyon suggests that the Redwall has been retreating at an average rate of 0.45 m/10^3 ^{14}C yr. This rate of cliff retreat, which is comparable to other cliff-retreat rates reported from arid environments, implies that the Colorado River cut through the Redwall Limestone in the vicinity of Horseshoe Mesa about 3.7 m.y. B.P.

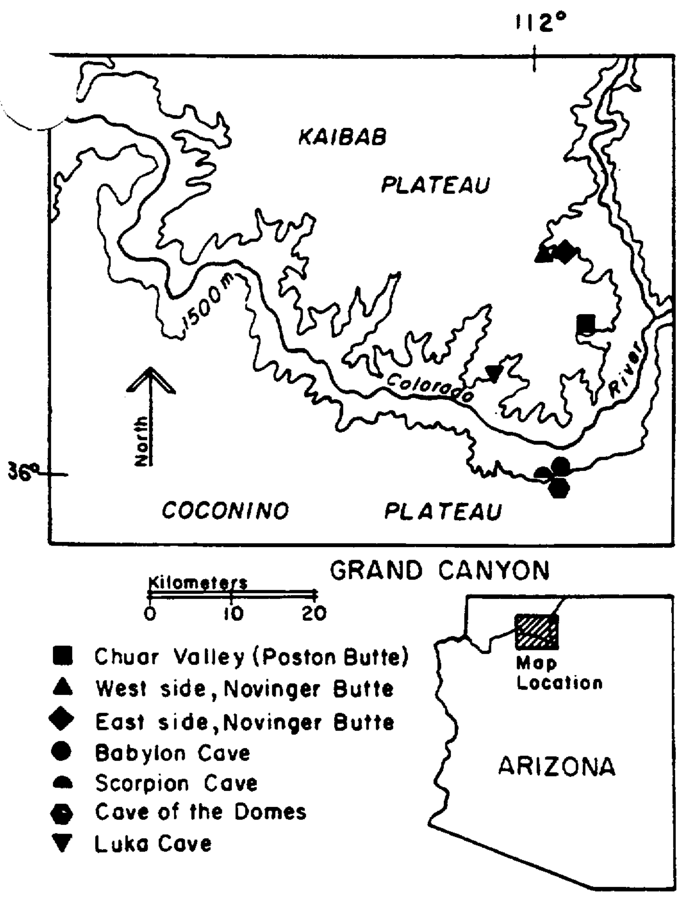


Figure 1. Location map of study area. Cave localities are marked by symbols.

INTRODUCTION

Packrat middens are debris piles left by packrats (*Neotoma* sp.), that contain fragments of local vegetation assemblages; thus, their study is important for paleoclimatologic research. In this report we attempt to explain the spatial distribution of packrat middens in caves and how the spatial distribution of these middens is related to rates of cliff retreat in the eastern Grand Canyon.

Packrat middens can be indurated by a coating of viscous packrat urine. Under dry conditions, the urine crystallizes, forming "amberat." The entire deposit may adhere to rock shelves and walls and survive more than 50,000 yr when protected from rain and high humidity.

Middens left by packrats inside rock crevices, in caves, and under cliff overhangs are commonly protected from destruction until the midden is exposed to weathering by cliff retreat. A midden of Pleistocene age can be preserved only if the midden is sufficiently far back in the crevice or cave or if the rate of cliff retreat is sufficiently slow that the midden is not exposed even after 10,000 yr or more of cliff retreat. Similarly, for a midden to be preserved under a cliff overhang, spalling of joint blocks or erosion of overhangs must be sufficiently slow or sufficiently infrequent to allow preservation of the midden. This reasoning is analogous to that employed in, for example, interpreting lichenometric data on the age of talus piles (Beschel, 1961).

Cole (1982) dated 53 packrat middens by the radiocarbon method and found Pleistocene middens in only two formations in the eastern Grand Canyon: the Cambrian Tapeats Sandstone and the Mississippian Redwall Limestone. The apparent absence of Pleistocene middens in upper Paleozoic formations (the Supai Group, the Coconino Sandstone, the Kaibab Limestone, and the Toroweap Formation) above the Redwall Limestone may suggest that their rates of cliff retreat are rapid enough to prevent the preservation of Pleistocene deposits in these noncavernous substrates. The abundance of Pleistocene deposits on ledges in the Tapeats Sandstone suggests that this substrate is retreating more slowly than are formations above the Redwall.

In this study we restrict our attention to the Pleistocene middens in small to medium caves (entrance less than 5 m diameter) formed in the Horseshoe Mesa Member of the Redwall Limestone in the eastern Grand Canyon (Fig. 1).

CLIFF RETREAT AND SURVIVAL OF PACKRAT MIDDENS

To estimate the rate of cliff retreat one must know the position of a datum relative to the cliff face at some time in the past. We think packrat middens are a suitable datum because they can

*Present address: Miami University, Oxford, Ohio 45056 be dated and their past positions estimated. Our argument centers on how the position of packrat middens relative to a cliff face nges with time and how such changes are related to cliff eat. To understand how the position of packrat middens can be estimated, we first examine the spatial distribution of modern packrat debris piles in caves.

Active packrat debris piles tend to be most common within 5 m of the cave entrance at a cliff face, and packrat activity extends farther back into the cave with diminishing frequency. Some packrat fecal pellets and plant debris are found as far back as 15 m into the cave. Presumably, most modern debris piles are unseen in small crevices and crawlways near the cave entrance—places safe from predators. Figure 2 illustrates a hypothetical frequency distribution of modern middens as a function of increasing distance from the cliff face. The relation between the position of packrat middens in a cave and the distance from the cave entrance is probabilistic; there is a high probability of a midden near the cave entrance and a declining probability of a midden farther back in the cave.

As the cave retreats, middens near the cave entrance will be destroyed, and younger middens will be deposited. The two processes of midden deposition and midden destruction through cliff retreat constantly change the age and spatial distribution of the middens in the cave. To unravel the effects of cliff retreat and midden deposition on the age composition and spatial distribution of middens in a cave, we assume that the frequency distribution of middens with distance from exposure at the cliff face takes some particular values, although the exact frequency distribution may vary somewhat from cave to cave and is unknown. Using a hypothetical frequency distribution, we shall illustrate how the spatial stribution of middens changes over time and how such changes are related to the rate of cliff retreat. For our purposes, we use a 0.4 m/10^3 yr rate of cliff retreat.

Figure 3 illustrates the spatial distribution of middens at different time intervals; each step shows the spatial distribution of middens at a given time. We assume that middens were deposited most commonly near the cliff face in the past because that is where active packrat debris piles are most abundant. The only other variable is cliff retreat. As shown in Figure 3b, the envelope of the distance-versus-age data points is diagnostic of cliff retreat; the slope of the envelope line gives the rate of cliff retreat.

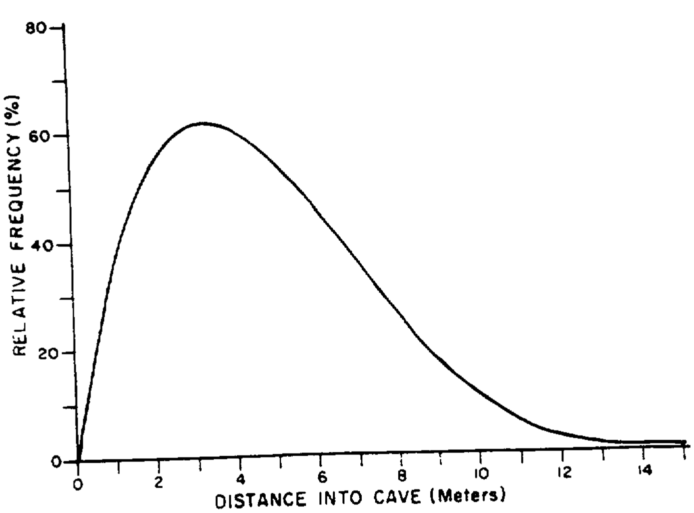
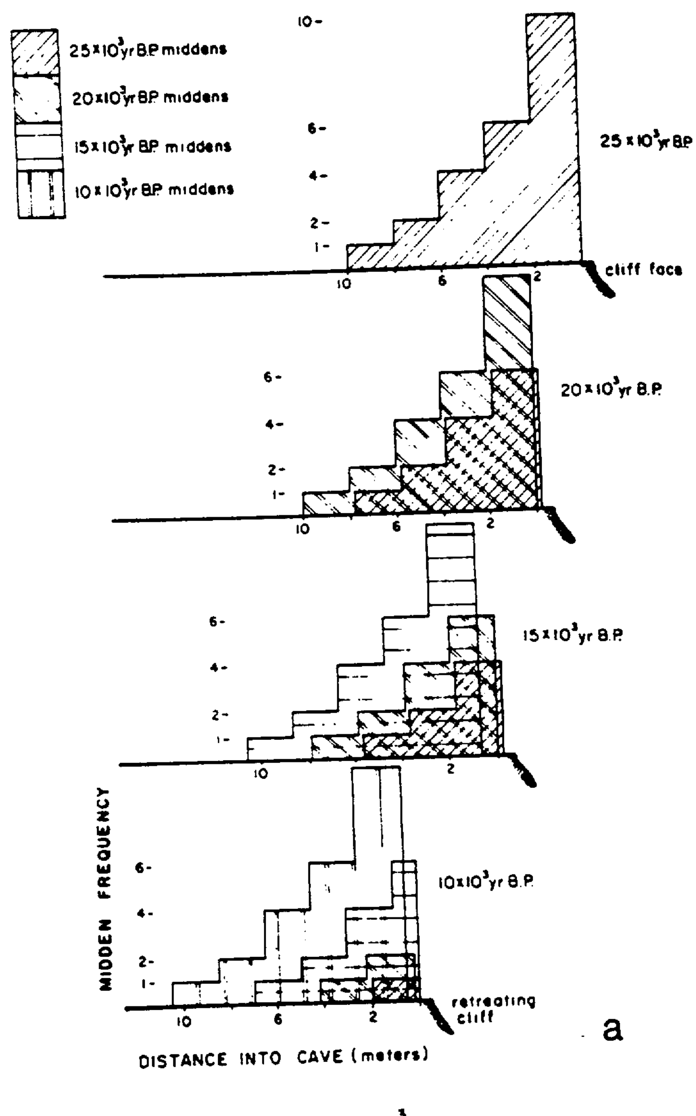


Figure 2. Ideal frequency distribution showing modern midden frequency with increasing distance from cliff face for hypothetical cave.

PLEISTOCENE MIDDENS IN THE REDWALL LIMESTONE

Direct application of our working hypothesis on midden distribution is not possible because we do not yet know how such variables as cave shape and size affect midden distribution. Furthermore, we would have to date all the middens in a cave—a procedure that would be extremely costly. Instead, we have sampled what appeared to be the oldest middens in each of several caves in the Redwall Limestone. Cursory examination of the plant fossils in a midden and of midden texture permits discrimination between Pleistocene and Holocene middens (Cole, 1981). Thus, we have probably sampled the middens situated near or at the envelope line in Figure 3.



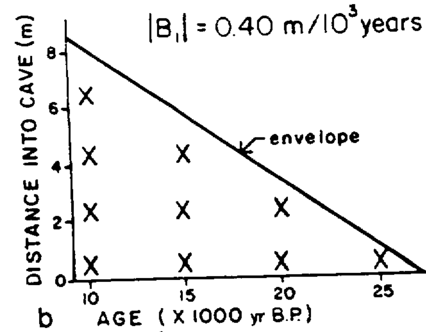


Figure 3. a: Packrat midden distribution over time in hypothetical cave using arbitrary 0.4 m/10^3 yr rate of cliff retreat. b: Resulting relation based on final distributions in a.

According to our reasoning, modern packrat dens may exist 15 m away from exposure in small to medium caves, whereas the limit of progressively older deposits should be nearer exposure at the cave entrance. Older middens that were deposited near the cave entrance have presumably been destroyed, and only those older middens that were deposited farther back in the cave are left. At least one other study (Phillips, 1977, p. 39) reported a cave in which the oldest deposits are nearest the entrance.

To see whether our line of reasoning yields plausible results, we have used regression analysis to estimate a relation between distance from the cave entrance and age of a midden: $Y = \beta_0 + \beta_1 X$.

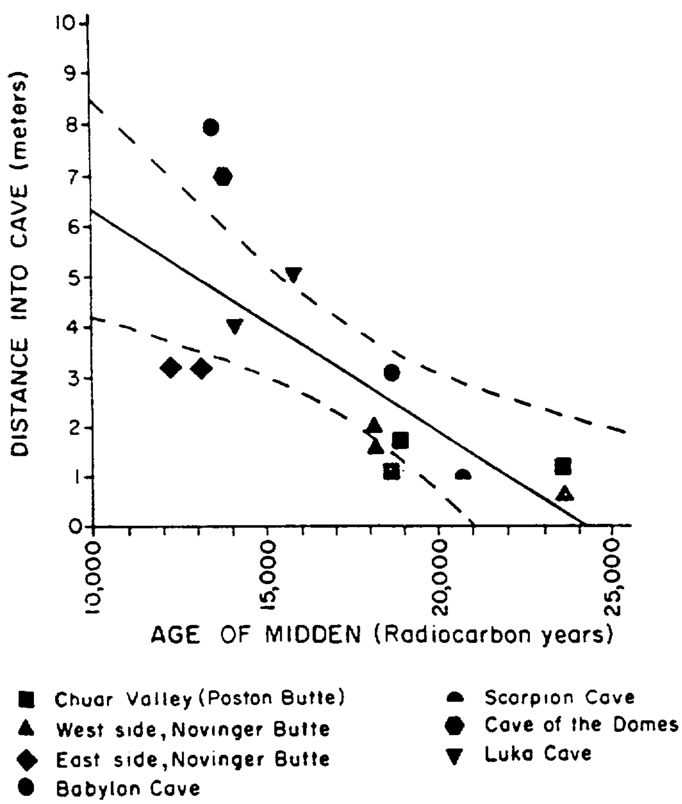


Figure 4. Regression line and its 95% confidence interval for 14 Pleistocene middens from Redwall Limestone.

TABLE 1. RATES OF CLIFF RETREAT IN ARID AREAS

Area	Rate of Cliff Retreat ($m/10^3$ yr)	Reference
Grand Canyon	0.18-0.72	
Mogollon Rim, Arizona	0.4-0.8	Mayer (1979)
Salt River, Arizona	0.4	P.E. Damon and others (unpub. data)
White River, Arizona	0.4	P.E. Damon and others (unpub. data)
Virgin River, Utah	0.3	P.E. Damon and others (unpub. data)
Colorado	0.2	Young (1974)
Colorado	0.6	Young (1974)
Sinai Peninsula	0.1-2.0	Yair and Gerson (1974)

where Y is the distance between a dated midden and the cave entrance (exposure), X is the age (in ^{14}C yr) of the oldest midden for a given distance from the entrance, β_0 is the expected maximum distance from exposure for modern middens, and β_1 is the rate of cliff retreat (m/10^3 yr).

We have estimated the envelope line by applying linear regression to the data from 14 Pleistocene middens collected from small to medium caves in the Horseshoe Mesa Member of the Redwall Limestone. The least-squares estimates of the regression coefficients (Fig. 4) differ significantly from zero at better than the 0.01 level of significance. The maximum expected distance from exposure for modern middens is 10.8 m. The estimate of the rate of cliff retreat for the Redwall Limestone is 0.45 m/10^3 ^{14}C yr. The range in our estimates of the rate of cliff retreat, at the 95% confidence level, is from 0.18 to 0.72 m/10^3 yr; these values are comparable to other estimates of cliff retreat in arid (sensu lato) areas (see Table 1).

If our estimate for the rate of cliff retreat, which is a 13,000-yr average rate, applies for longer intervals, then our data imply that the Colorado River cut through the Redwall Limestone near Horseshoe Mesa between 9.3 and 2.3 m.y. B.P., if we use 0.18 and 0.72 m/10^3 yr, respectively, and probably 3.7 m.y. B.P. on the basis of a 0.45 m/10^3 yr rate of cliff retreat. These estimates are consistent with previous age estimates for the Grand Canyon (McKee and others, 1967; Lucchitta, 1979).

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ACKNOWLEDGMENTS

Reviewed by D. P. Adam, J. P. Bradbury, P. S. Martin, and C. M. Wentworth. Partially funded by National Science Foundation Grant DEB 79-23840 to Paul S. Martin. Radiocarbon dates were provided by the University of Arizona Laboratory of Isotope Geochemistry.

Manuscript received March 24, 1982
Revised manuscript received June 28, 1982
Manuscript accepted June 29, 1982